12

AD F300366

ADA136645

MEMORANDUM REPORT ARBRL-MR-03324

COMPUTER SIMULATION OF SCALED MARK84 BOMB IMPACT INTO CONCRETE

Kent D. Kimsey
George H. Jonas
Jonas A. Zukas

November 1983

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER

BALLISTIC RESEARCH LABORATORY

ABERDEEN PROVING GROUND, MARYLAND

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MEMORANDUM REPORT ARBRL-MR-03324	2. GOVT ACCESSION NO. AD-A136645	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) COMPUTER SIMULATION OF SCALED MARK84 BOMB IMPACT INTO CONCRETE		5. TYPE OF REPORT & PERIOD COVERED FINAL
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) K. D. KIMSEY G. H. JONAS J. A. ZUKAS		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS US Army Ballistic Research Laboratory, ARDC ATTN: DRSMC-BLT(A) Aberdeen Proving Ground, MD 21005		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L162618AH80
11. CONTROLLING OFFICE NAME AND ADDRESS US Army AMCCOM, ARDC Ballistic Research Laboratory, ATTN: DRSMC-BLA-S(A) Aberdeen Proving Ground, MD 21005		12. REPORT DATE November 1983
		13. NUMBER OF PAGES 50
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

MARK84	Numerical Simulation
Ricochet	Impact
Penetration	Concrete
Bomb	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents the results of three-dimensional finite element analyses of a scaled (1/15) MK84 bomb impacting thick concrete targets at large obliquities. Two bomb structures were modeled, one of solid steel and another with an 0.2cm steel wall, the cavity being filled with an inert simulant to represent the explosive tritonal. The analysis covers the latter one. The computations were performed with EPIC-3, a three-dimensional finite element program for the study of wave propagation and impact in homogeneous isotropic and anisotropic materials, as well as concrete. The critical impact angle for delineating

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

penetration and ricochet is determined as a function of bomb structure and obliquity. These prove to be in close agreement with experimental results. Some comments on computational approaches for rapid, cost-effective numerical studies of such situations conclude the paper.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (cont'd)

I. INTRODUCTION

Recently, there has been a renewed interest in bombs impacting concrete targets and their trajectory through the target. This is especially important when the bomb is equipped with a delay fuze. Experimental firings conducted by Roecker[1] of 1/15th scale MARK84 (MK84) bombs impacting thick concrete targets at various obliquity angles and striking velocities have shown the bomb to follow one of two trajectories:

(a) penetration - piercing of the target by the bomb. In some of the tests, partial penetration of the target was observed followed by ejection of the bomb from the crater and tumbling once clear of the target. This behavior is termed rebound.

(b) ricochet - deflection of the bomb from the target surface in which the nose of the bomb is never completely embedded in the target. A subset of ricochet is broaching wherein the bomb tunnels through the target along a trajectory parallel to the target surface, and after sometime it turns towards the target surface and exits.

The experiments conducted by Roecker[1] established critical obliquity angles for delineating penetration and ricochet as a function of striking velocity for solid and thin-walled MK84 bombs. The bombs were inscribed by a polypropolux sabot and fired from a 57mm smooth-bore launcher at velocities from 150 m/s to 270 m/s. The concrete targets which were 15.24cm thick and approximately 1 meter square were placed at obliquities from 20° - 40°. The experimental evidence consists of post-impact measurements, flash radiographs, polaroid photographs, and some movies. Figure 1 shows a schematic of the thin-walled bomb. The solid bomb, which was fired to investigate the influence of wall thickness on the critical obliquity angle, has the same external dimensions.

Figure 2 is a photograph of typical pre- and post-impact conditions for a thin-wall bomb impacting the concrete target at 159 m/s at an obliquity of 31°. This happens to be a ricochet mode and the ogival nose essentially remains undeformed. What appears to be an indentation in photograph near the nose is a scar not a localized plastic deformation. The deformation near the rear of the bomb is the result of the tail of the bomb "slapping" the target in the late stages of the ricochet event.

To gain further insight into characterizing the mechanisms of the impact event which distinguish the different modes of penetration, numerical simulation of scaled MK84 bomb impacts have been performed using the EPIC-3[2] code. The results of these simulations are discussed and compared with experimental observations.

---

1 *E. T. Roecker, et. al., BRL Report in progress.*

2 *G. R. Johnson, D. J. Vavrick, and D. D. Colby, "Further Development of EPIC-3 for Anisotropy, Sliding Surfaces, Plotting and Material Models," Ballistic Research Laboratory, ARBRL-CR-00429, May 1980 (AD B048305L).*

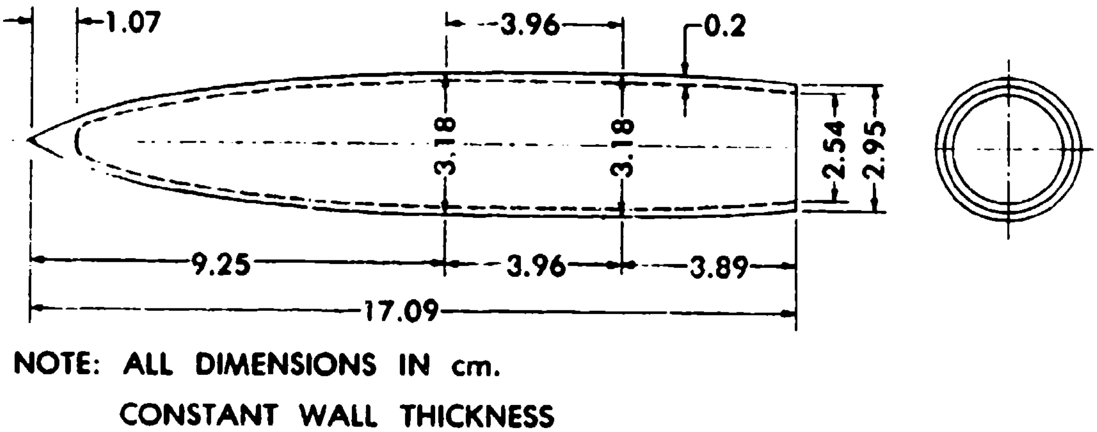

Figure 1. Scaled MARK84 Thin-Wall Bomb

Figure 2. Pre- and Post-Impact Conditions for Thin-Wall Bomb Impacting Concrete Target at 31° Obliquity at 159 m/s

II. NUMERICAL MODEL

The thin-walled bomb has been modelled with four rings of elements with the outer ring of elements representing the 2mm steel casing. The inner rings of elements represent the inert simulant to represent the explosive tritonal. The bomb contains 855 nodes and 3456 elements and the entire model is comprised of 8070 nodes and 39,744 constant strain tetrahedral elements.

A deep penetration "tunneling" model has been employed for treatment of the sliding surface. The bomb has been declared the master and the target has been declared the slave. This is the reverse of that employed by Johnson.[3]

The constitutive model in EPIC-3 employs an incremental elastic-plastic relationship using the von-Mises yield criterion to describe the deviatoric behavior of materials. Provision is made to account for strain rate, temperature, and strain hardening effects. Thermal softening and strain rate effects were not taken into account due to lack of data to support such models. The hydrostatic component of stress is obtained from the Mie-Gruneisen equation of state for the steel casing and explosive simulant.

A plain (unreinforced) concrete equation of state which is valid up to 30 GPa was used to model the concrete. The concrete model is discussed in References 2 and 4 and is presented briefly here for completeness. The concrete model is constructed from Hugoniot data by Gregson[5] and static yield strength data from Chinn and Zimmerman.[6] The aggregate used in Gregson's work had an average diameter of 3.2mm and an average initial density of 2.185 g/cm^3. The concrete consisted of 18% voids, 25% granite, 20-25% quartz grains, and 25-30% cement paste by volume.

The pressure-volume relationship for the concrete model is shown in Figure 3. The estimated unloading path is one which permits the concrete to return to its solid density (2.6 g/cm^3) when loaded past the point where all voids have collapsed, $\mu = 0.3$.

---

3 *G. R. Johnson, Honeywell Inc., Defense Systems Division, Private communication.*

4 *J. J. Osborn and D. A. Matuska, "Dynamic Response of a Kinetic Energy Penetrator, Vol II. - Hydrocode Analysis," AFATL TR 78-24, March 1978.*

5 *V. G. Gregson, Jr., "A Shock Wave Study of Fondu-Frye WA-1 and a Concrete," DNA report 2797F, February 1972.*

6 *J. Chinn and R. M. Zimmerman, "Behavior of Plain Concrete Under Various High Triaxial Compression Loading Conditions," AFWL TR 64-163, August 1965.*

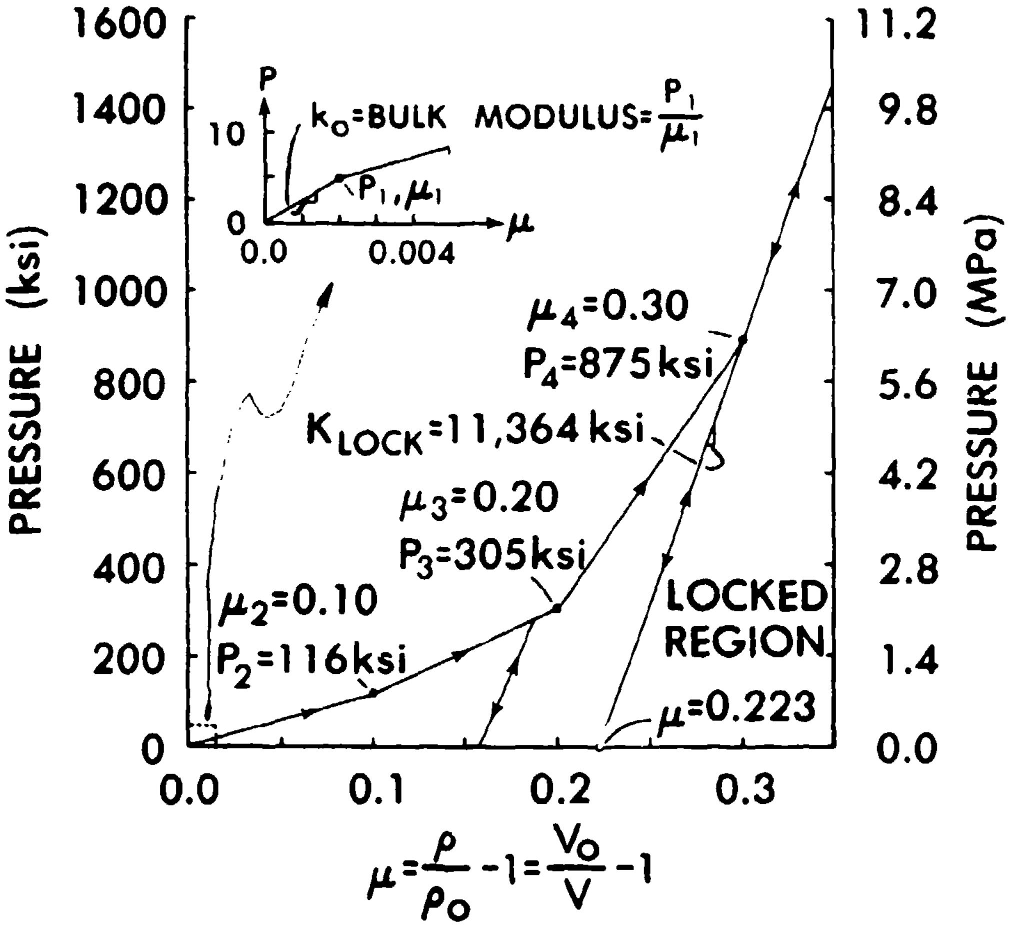

Figure 3. Pressure-Volume Relationship for Concrete Model

The unloading path is a straight line which connects with the load curve at the point where all the voids have collapsed and has a slope equal to that of the load curve at the point where total void collapse occurs. For values of excess compression below that where void collapse is initiated (μ = .002), loading, unloading, and reloading occur along the same elastic path. For values of excess compression between these extremes, the bulk modulus is assumed to vary linearly between K_0 and K_{LOCK}.

The concrete model has been extensively and successfully employed by the Air Force Armament Laboratory for penetrations in the 60 to 300 m/s velocity range.[4] A detailed description of the model can be found in References 2 and 4. Other pertinent literature is found in References 7 and 8. The use of the model should be limited to calculations with an impedance mismatch, such as steel and concrete in this case, because the model assumes no transmission of shock waves from the concrete into the penetrator.

In the calculations presented here the bomb elements were not permitted to fail. However, the concrete elements were completely failed, at which point the element no longer supports a pressure or tensile stress, when its equivalent plastic strain exceeded 30 percent. It should be noted that preliminary calculations which raised the equivalent plastic strain from 10-30 percent showed no distinct differences in target crater profile.

III. DISCUSSION OF RESULTS

Computations were performed for the thin-walled structure (Figure 1) at obliquity angles of 25.7°, 30°, and 33.8° with a striking velocity of 228 m/s. These obliquity angles and striking velocity were chosen due to the availability of experimental data. The experimental data indicated that with a striking velocity of 228 m/s the 25.7° impact has a 50% probability of ricochet and a 50% probability of rebound. The higher obliquity angles resulted in ricochet or broaching.

It should be noted that in light of the excessive amount of computer time required by these calculations the solid bomb has not been extensively pursued and the results herein pertain to the thin-walled structure only. The explicit integration scheme employed in EPIC-3 required approximately 85 cp seconds per microsecond of simulation on a CDC Cyber 76 for the results presented herein.

Figure 4 shows the deformation profiles for the three different obliquity angles at the time where maximum penetration is achieved. Appendix A contains a complete temporal sequence of deformation profiles for the different obliquities. In general, the deformation profiles in Figure 4 closely resemble those observed in the experiments. The discontinuity in the nose of the bomb is an artifact of the sliding surface technique. The target crater profiles, in the symmetry plane, are delineated by elements which have not exceeded an equivalent plastic strain of 30 percent.

---

[7] *D. McHenry and J. Karni, "Strength of Concrete Under Combined Tensile and Compressive Stress," American Concrete Institute, page 54, 10 April 1958.*

[8] *K. E. Crawford, C. J. Higgins, and E. H. Bultmann, "The Air Force Manual for Design and Analysis of Hardened Structures," AFWL TR-74-102, October 1974.*

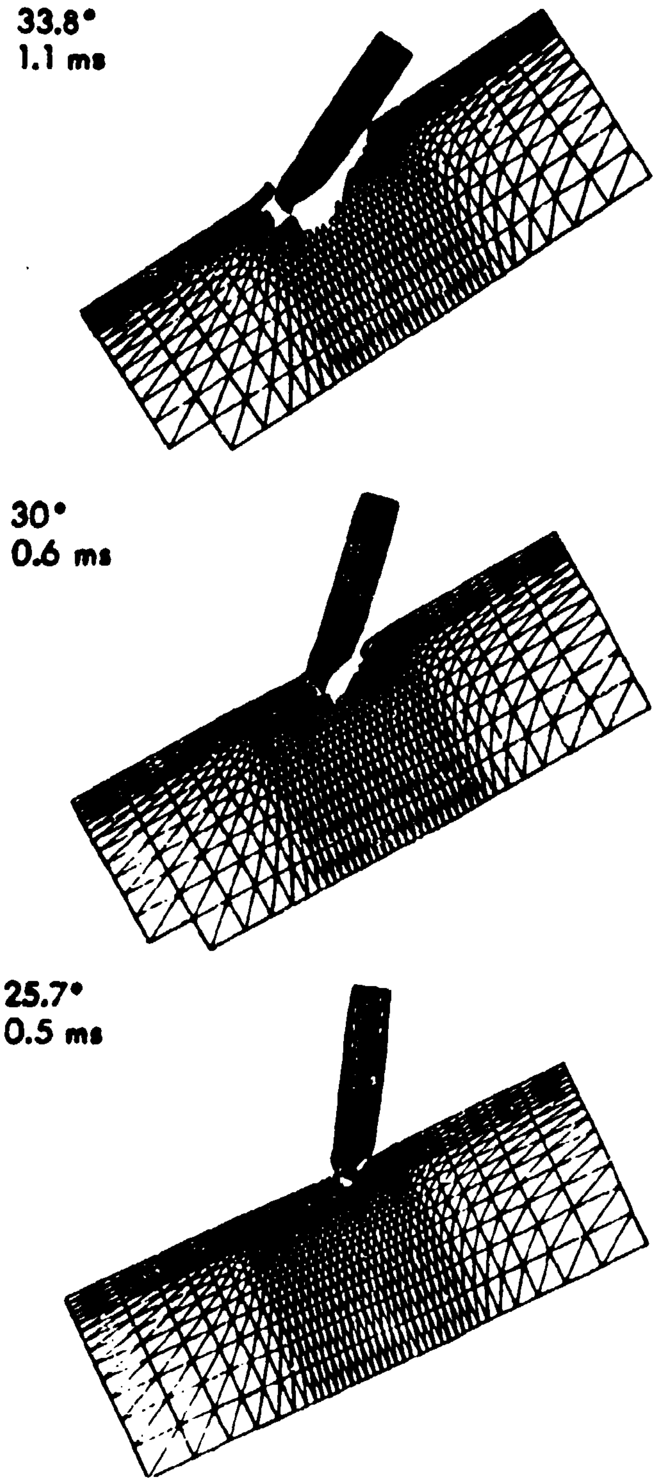

Figure 4. Deformation Profiles for Thin-Wall Bomb at Indicated Obliquities

The net velocity and angular velocity histories for the different obliquities are compared in Figures 5 and 6, respectively. As can be seen in Figure 5, at approximately 0.3ms the net velocity of the 25.7° impact starts to increase. Furthermore, the vertical component of velocity changes sign. This, in our opinion, is indicative of a rebound mode. One can also note the slower deceleration of the higher obliquity impacts.

The comparison of angular velocity, i.e. the rate at which the tail of the bomb is falling towards the target, histories for the different obliquities presented in Figure 6 show that the higher obliquity impacts result in a large angular acceleration being imparted to the bomb. In fact, the 33.8° impact has been carried out beyond one millisecond at which time there appears to be a steady state angular velocity of 500 rad/s and the net velocity has been reduced to approximately 10% of the striking velocity. This angular velocity history for the 33.8° impact coupled with the deformation profile at 1.1ms (see Figure 4 which indicates the initiation of tunneling) indicates a broaching mode, in our opinion. The intermediate obliquity is felt to be a ricochet mode in that no tunneling behavior has been observed out to 600 ms.

The response of the thin-walled bomb at the various obliquities is further compared in Figures 7-9 which show the time history of bending moment, shear stress, and axial load, respectively, for the indicated obliquities. These temporal histories are for the layer of elements in the cylindrical portion of the bomb just above the ogival nose. No distinct difference is noted for distinguishing penetration and ricochet based on the temporal histories for bending moment and shear stress. However, the reduction in axial load beyond 0.3ms for the 25.7° obliquity (Figure 9), in conjunction with the corresponding net velocity history (Figure 6), is indicative of "rebounding."

IV. SUMMARY

Shortly after impact, an angular acceleration is imparted to the bomb and the magnitude and duration of this angular acceleration is proportional to the incidence angle. Eventually, the angular acceleration imparted to the bomb reaches a steady state. A large steady state angular velocity appears to be characteristic of a broaching mode of penetration accompanied by slower deceleration of the bomb.

The computer simulations presented here predict the critical angle for ricocheting within 3-5°. They are quite expensive (80-90 CPU seconds/1 μs of real time). This is due principally to the fact that explicit integration is used throughout. While accuracy considerations require a time step characteristic of explicit integration schemes during the early stages of impact (0-100 μs), low impact velocity computations such as these could be conducted far more economically by switching to an implicit scheme once details of wave motion are no longer important. The principal advantage of codes such as EPIC-3 for these applications is their ability to supplement the meager information obtained from impact experiments. The judicious combination of computations and experiments can lead to effective designs with cost and efficiency factors below those from either technique alone.

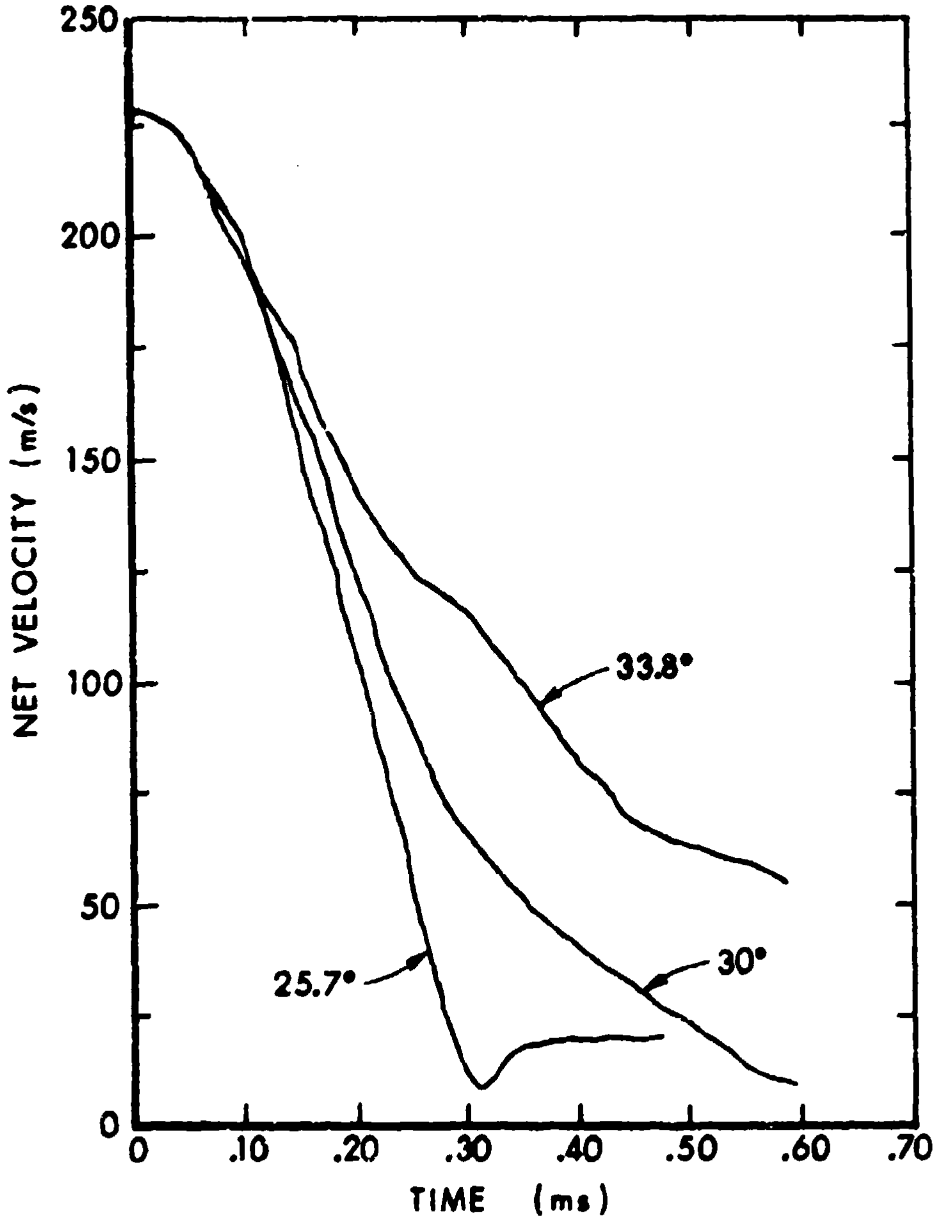

Figure 5. Net Velocity History for Thin-Wall Bomb

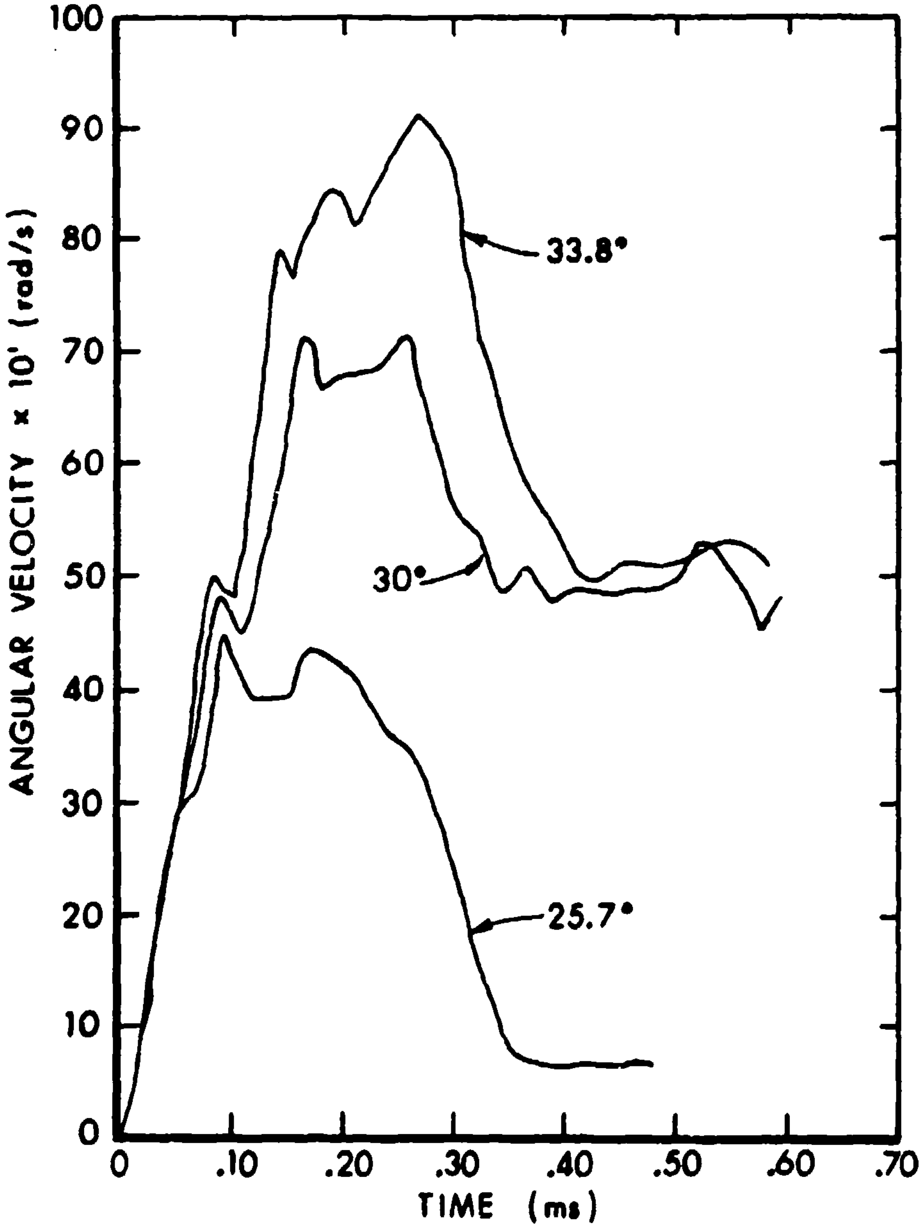

Figure 6. Angular Velocity History for Thin-Wall Bomb

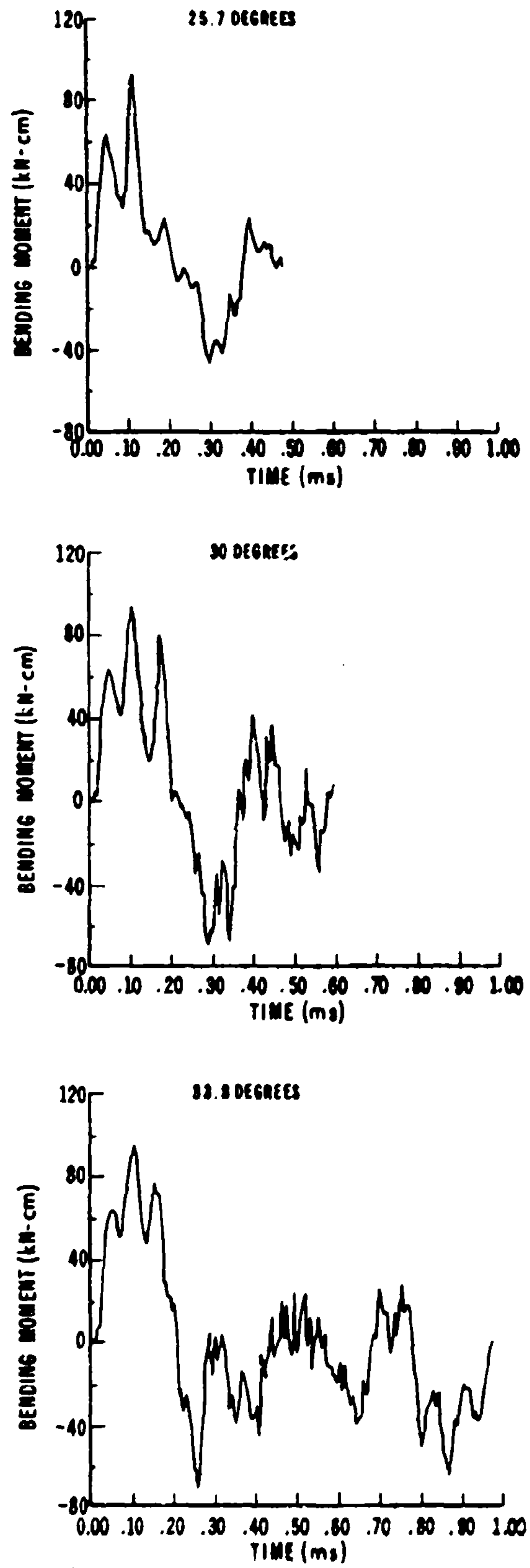

Figure 7. Bending Moment History for Thin-Wall Bomb at Indicated Obliquities

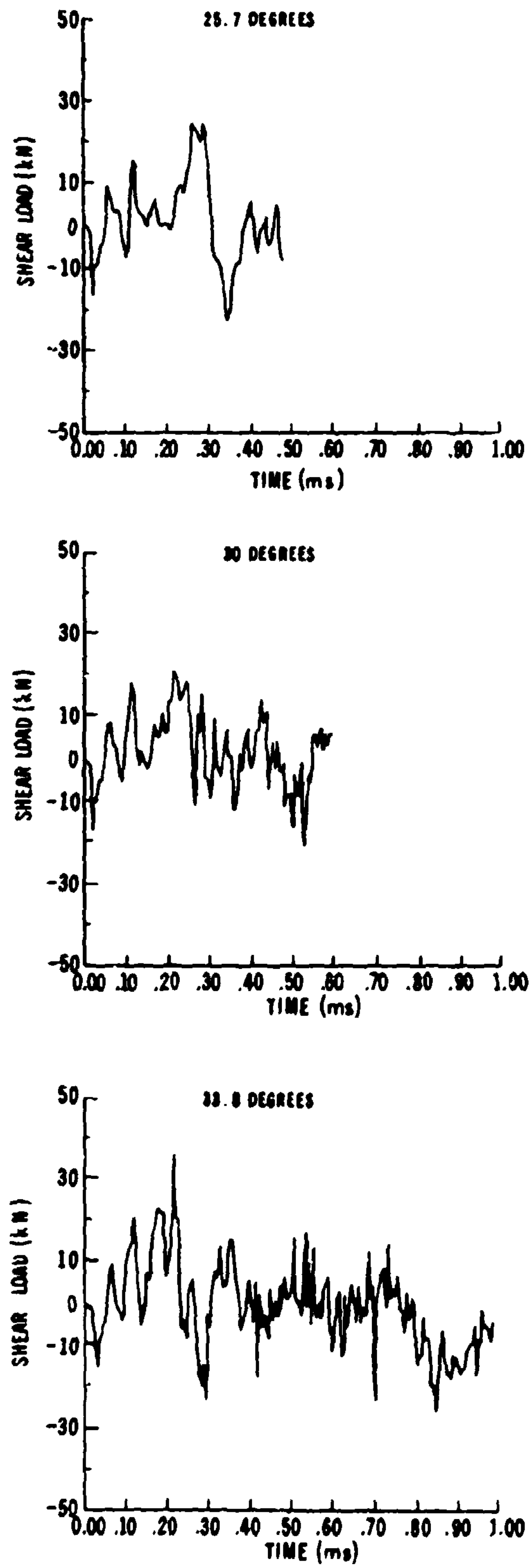

Figure 8. Shear Stress History for Thin-Wall Bomb at Indicated Obliquities

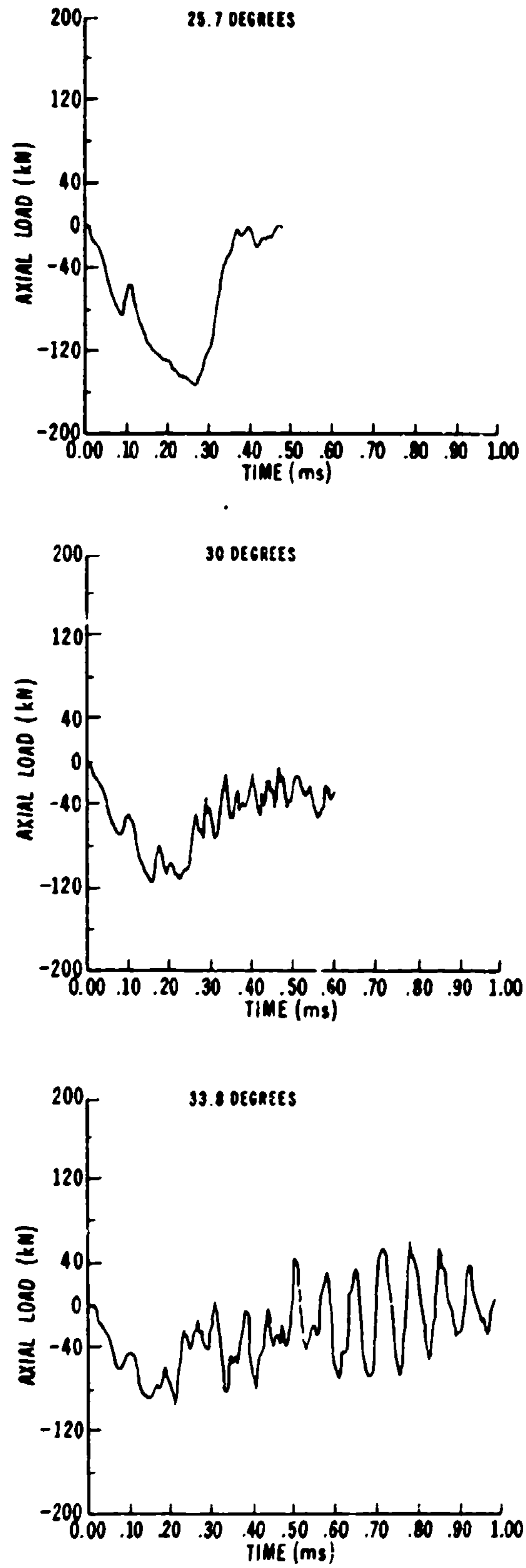

Figure 9. Axial Load History for Thin-Wall Bomb at Indicated Obliquities

APPENDIX A

Temporal Sequence of Deformation Profiles

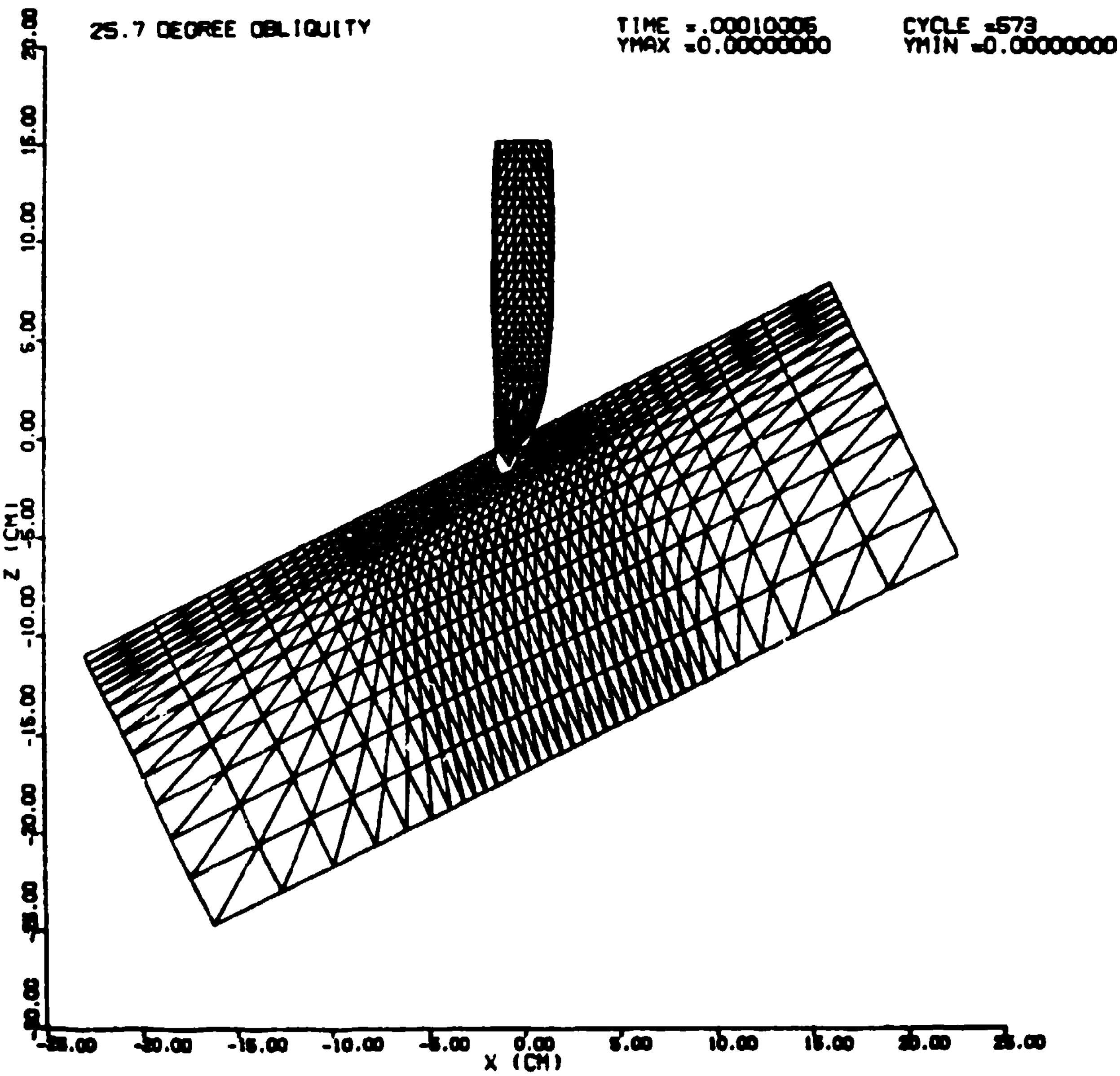

Figure A1. Deformation Profile for 25.7° Obliquity at T = 10 μs

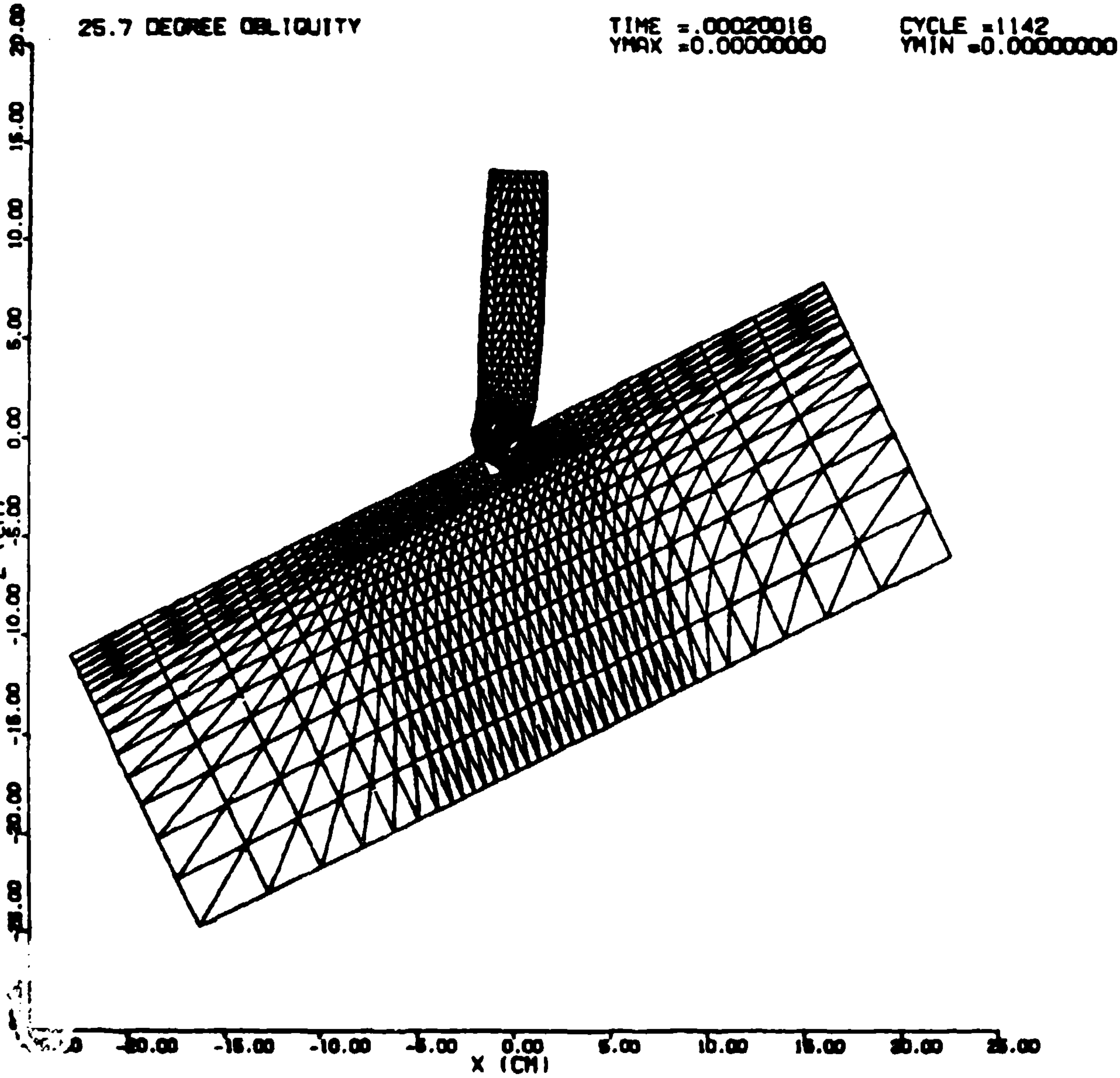

Figure A2. Deformation Profile for 25.7° Obliquity at T = 20 μs

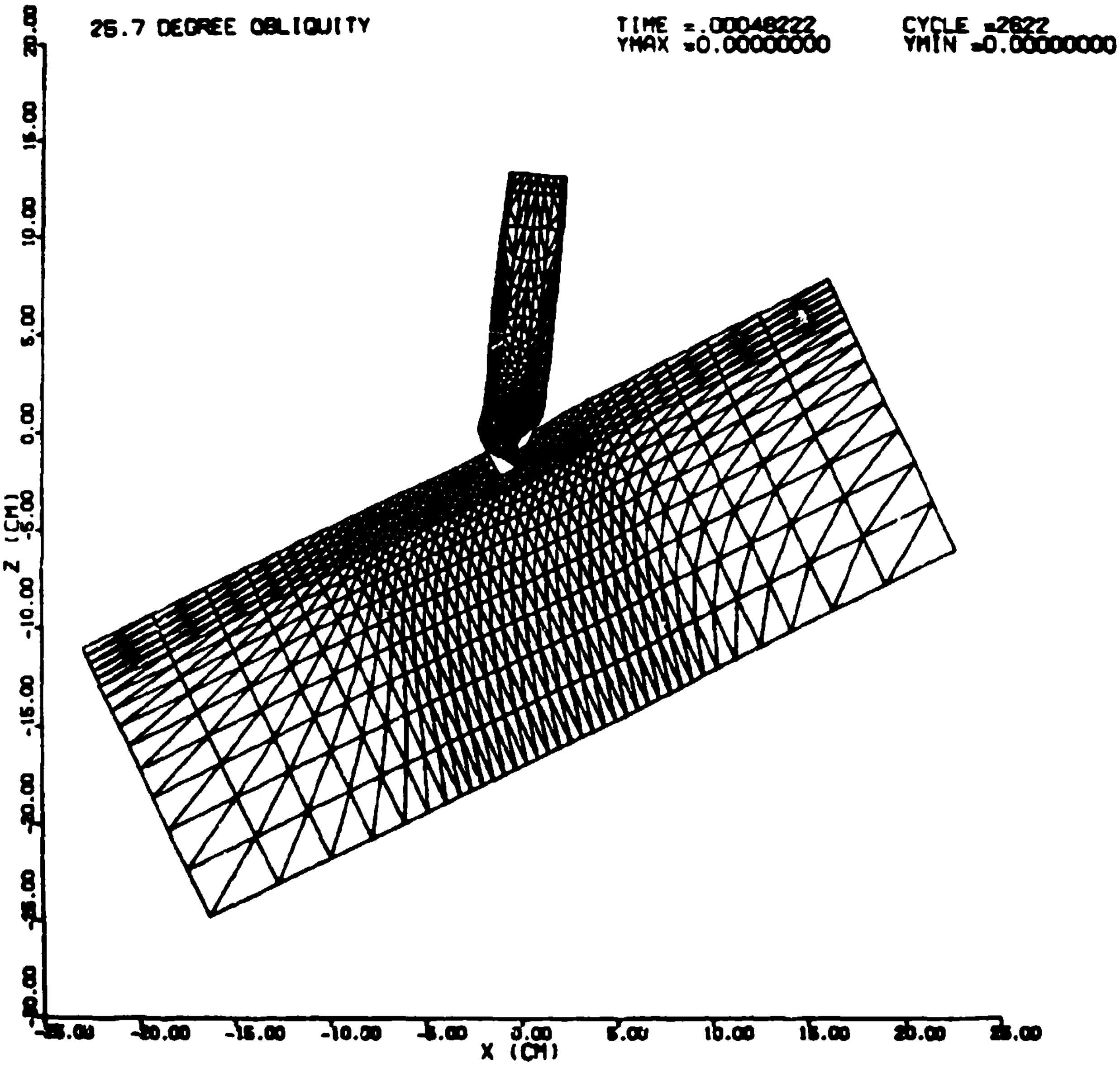

Figure A3. Deformation Profile for 25.7^{o} Obliquity at T = 48.2 μs

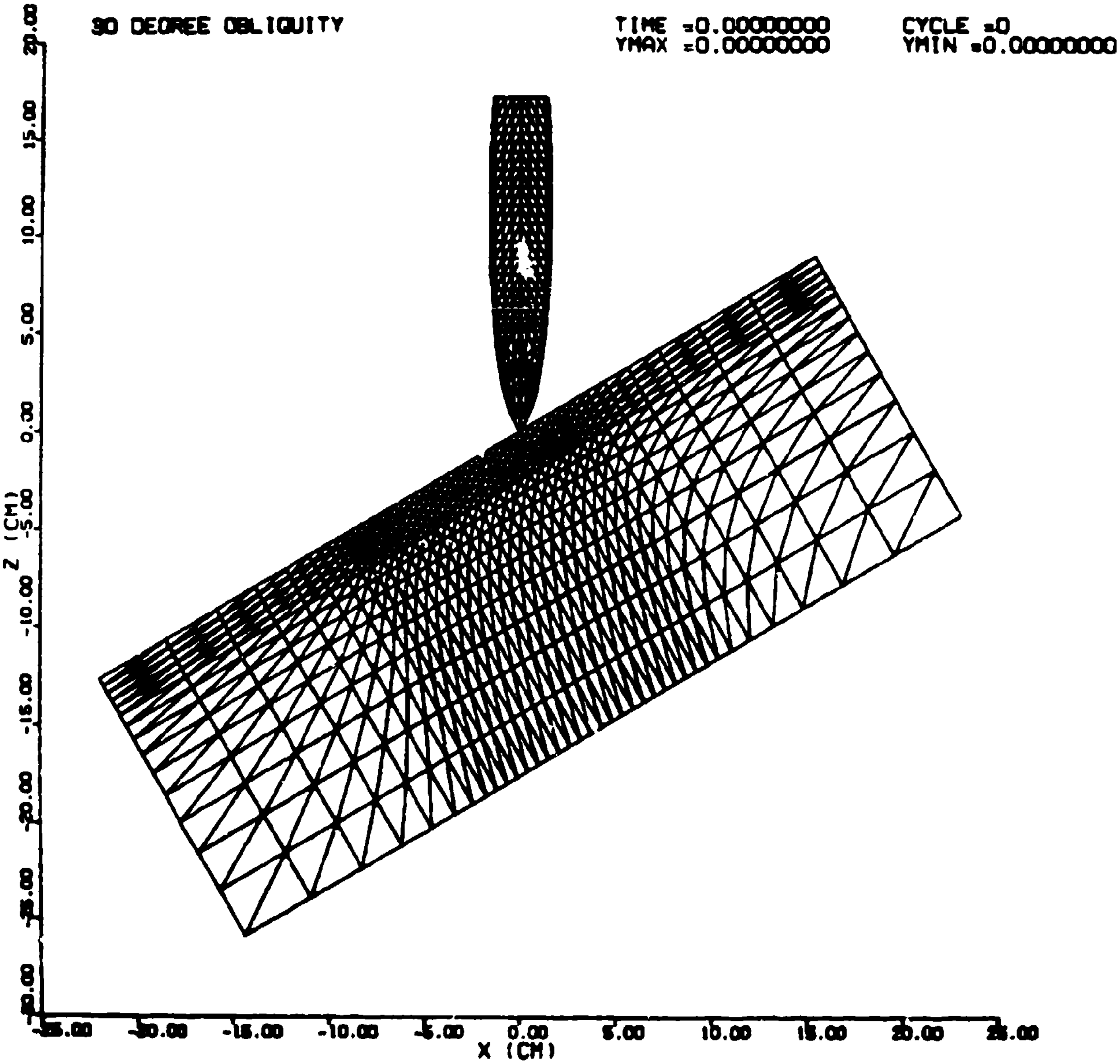

Figure A4. Deformation Profile for 30^{o} Obliquity at T = 0 μs

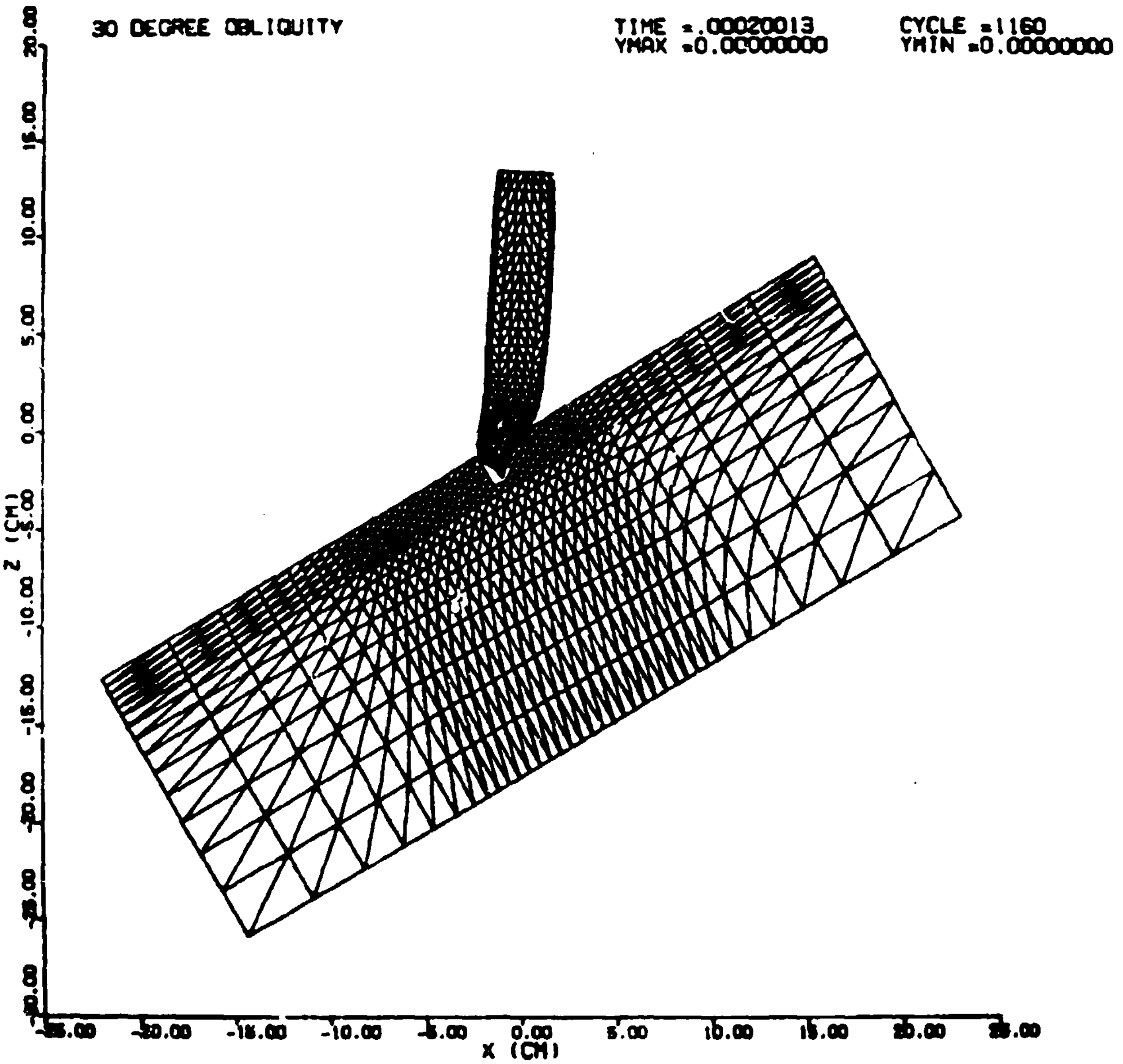

Figure A5. Deformation Profile for 30° Obliquity at T = 20 μs

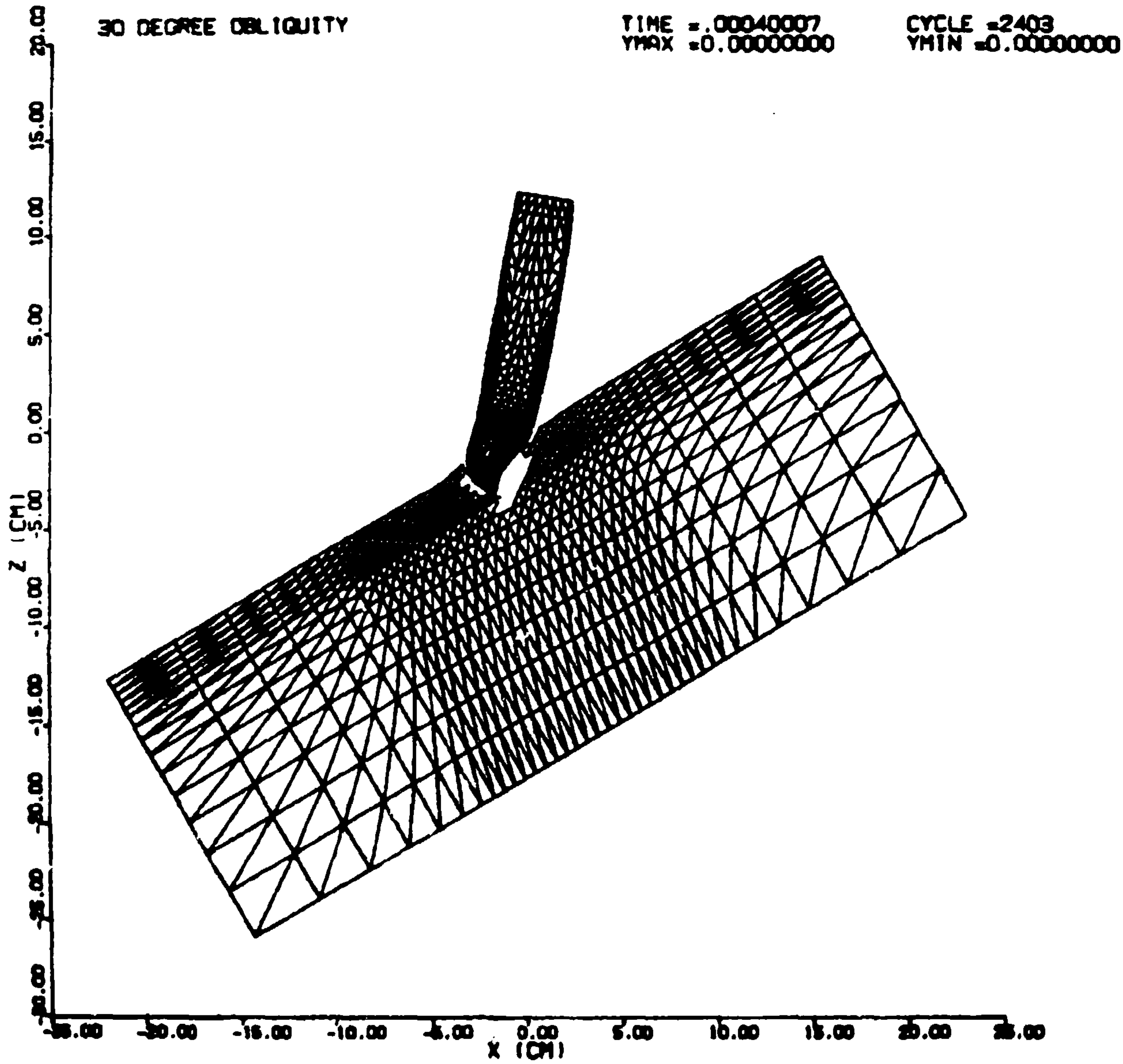

Figure A6. Deformation Profile for 30° Obliquity at T = 40 μs

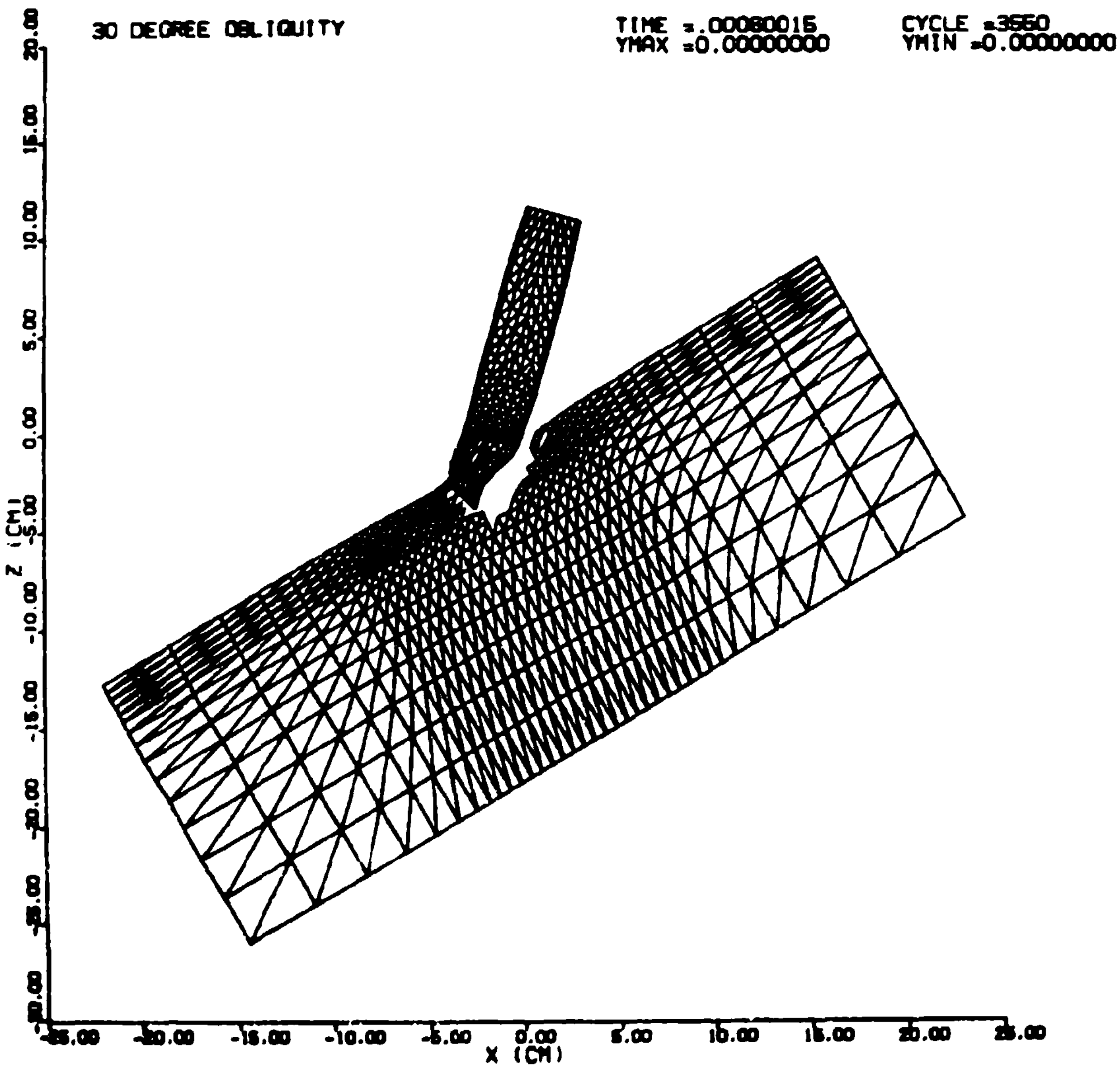

Figure A7. Deformation Profile for 30° Obliquity at T = 60 μs

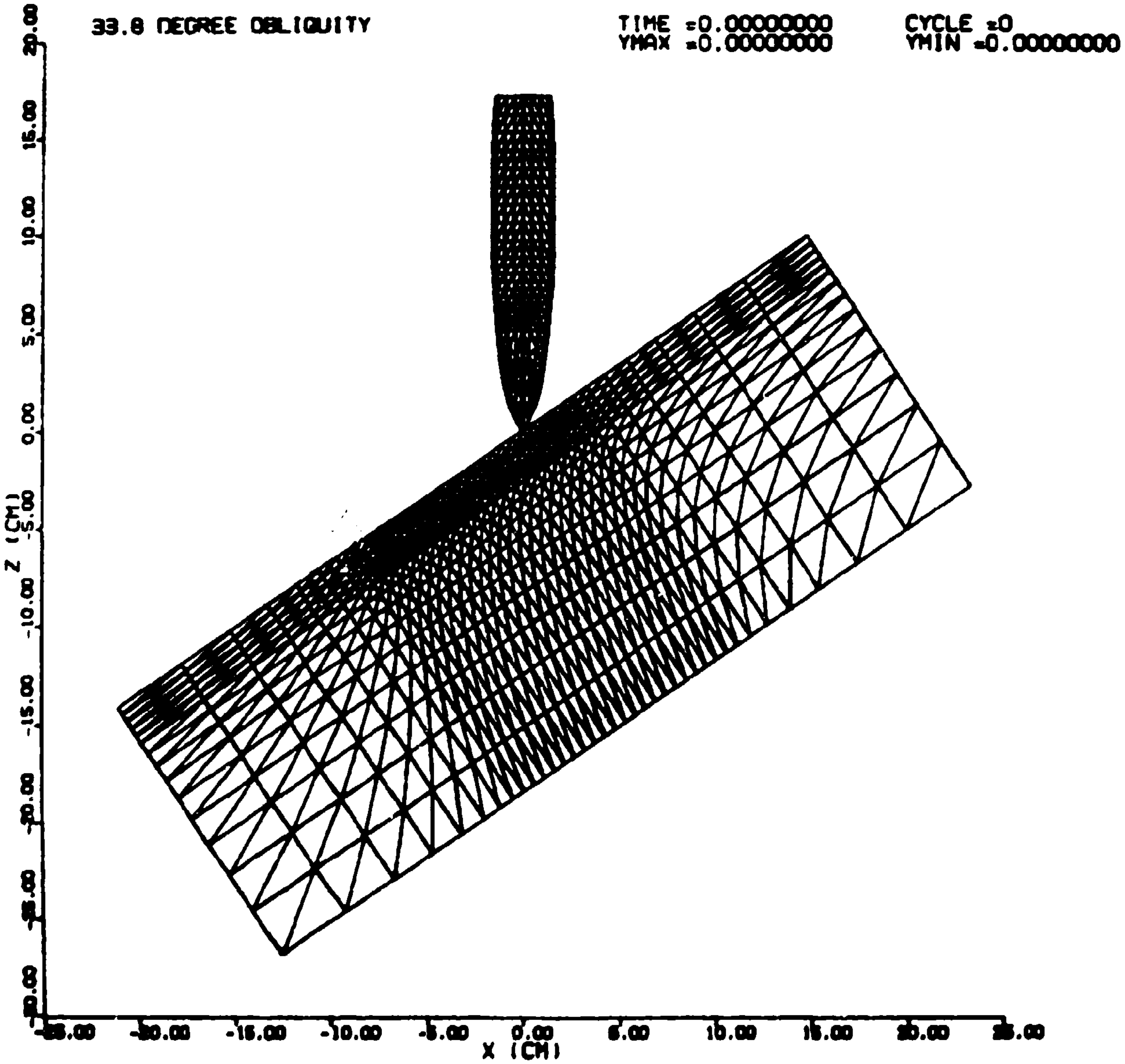

Figure A8. Deformation Profile for 33.8° Obliquity at T = 0 μs

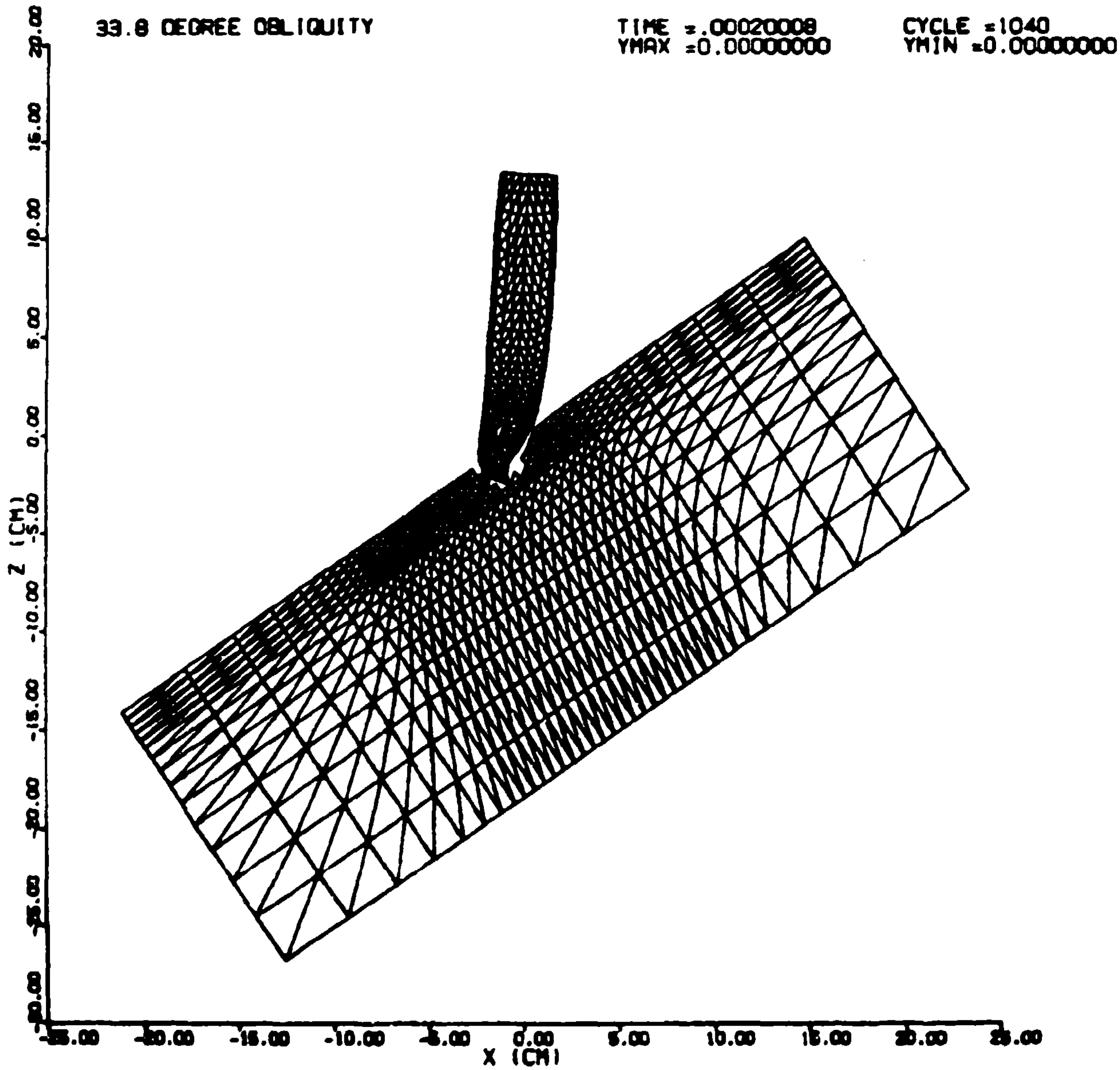

Figure A9. Deformation Profile for 33.8° Obliquity at T = 20 μs

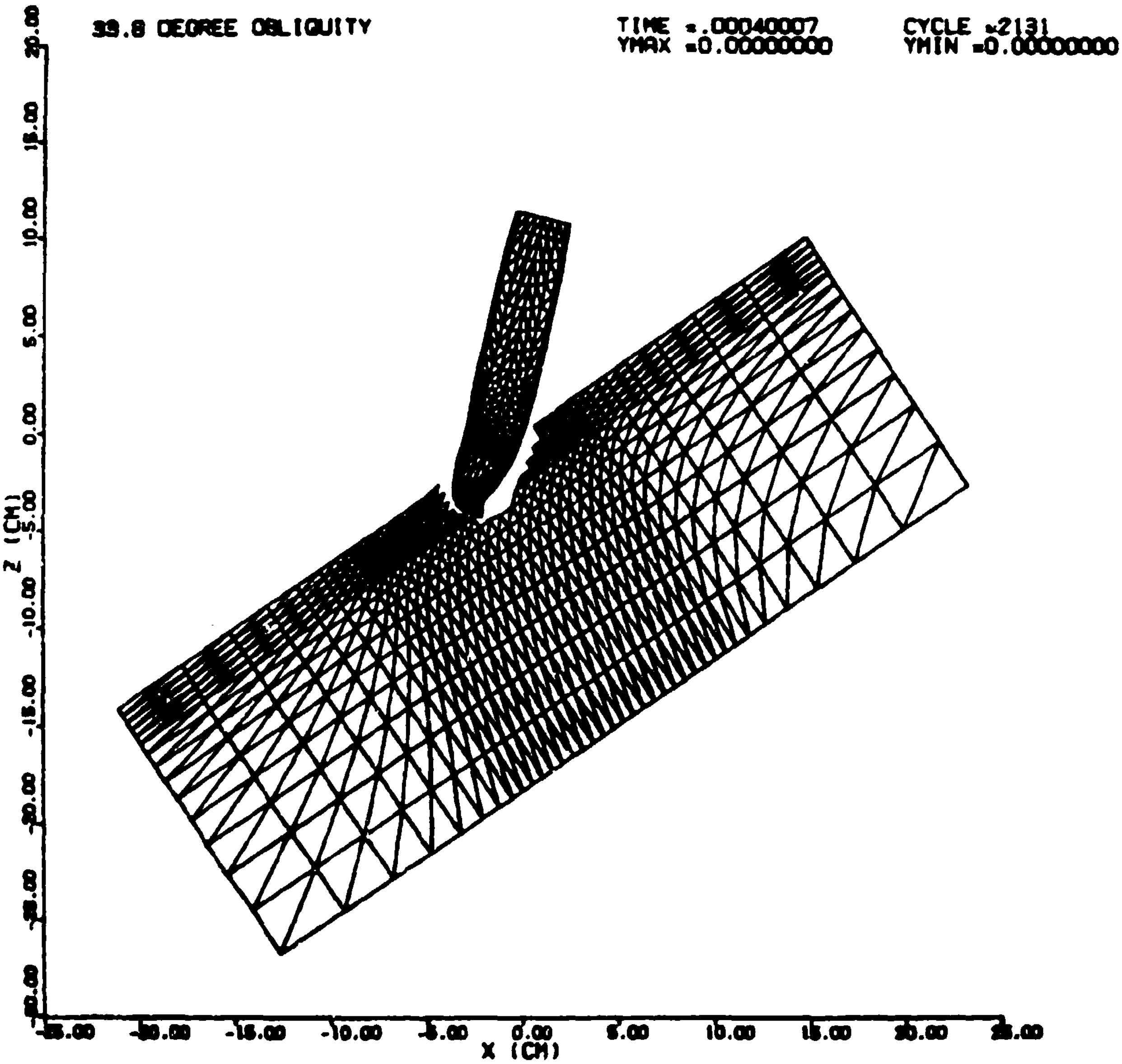

Figure A10. Deformation Profile for 33.8° Obliquity at T = 40 μs

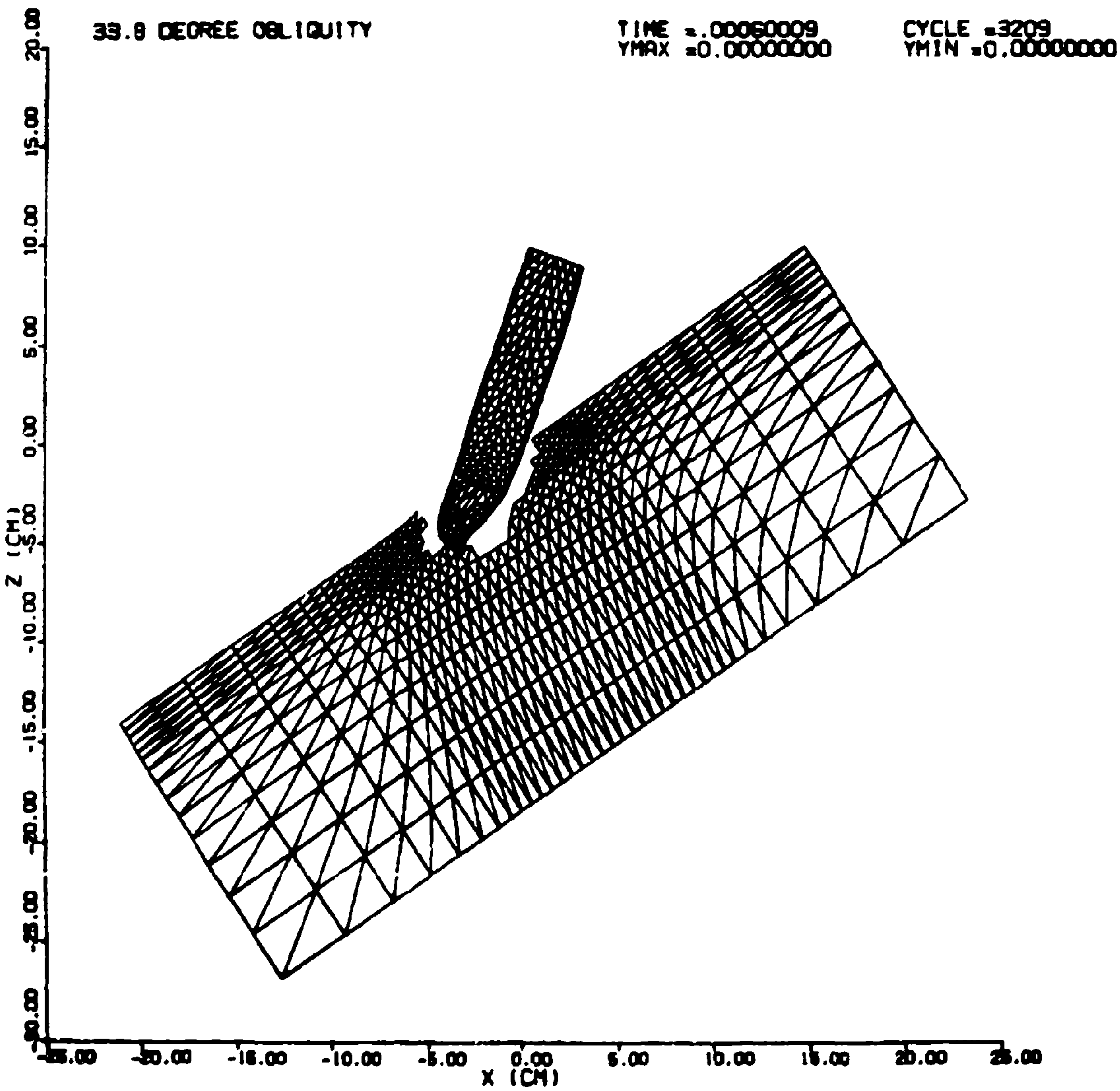

Figure A11. Deformation Profile for 33.8^{o} Obliquity at $T = 60\ \mu s$

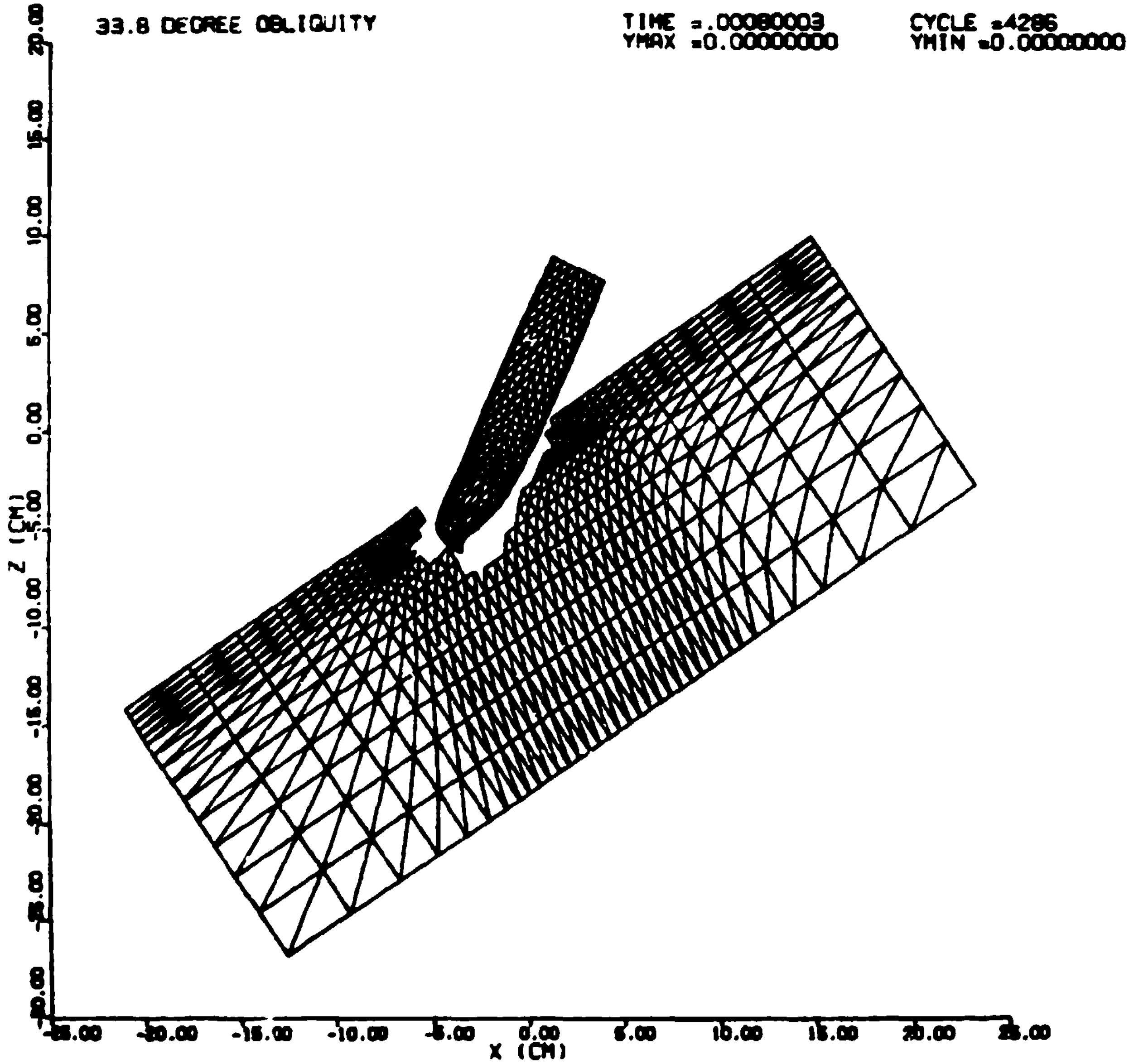

Figure A12. Deformation Profile for 33.8° Obliquity at T = 80 μs

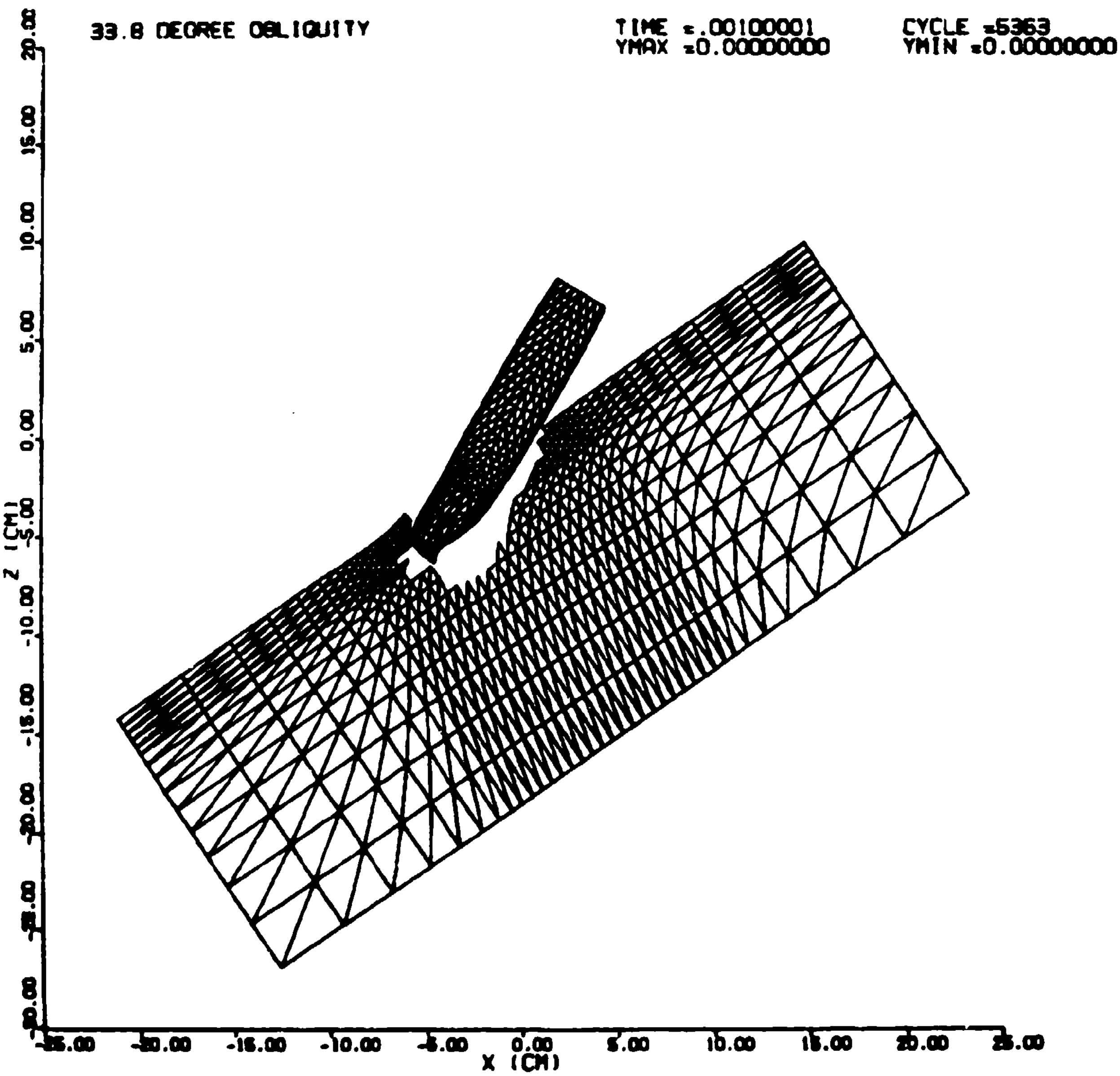

Figure A13. Deformation Profile for 33.8^{o} Obliquity at T = 100 μs

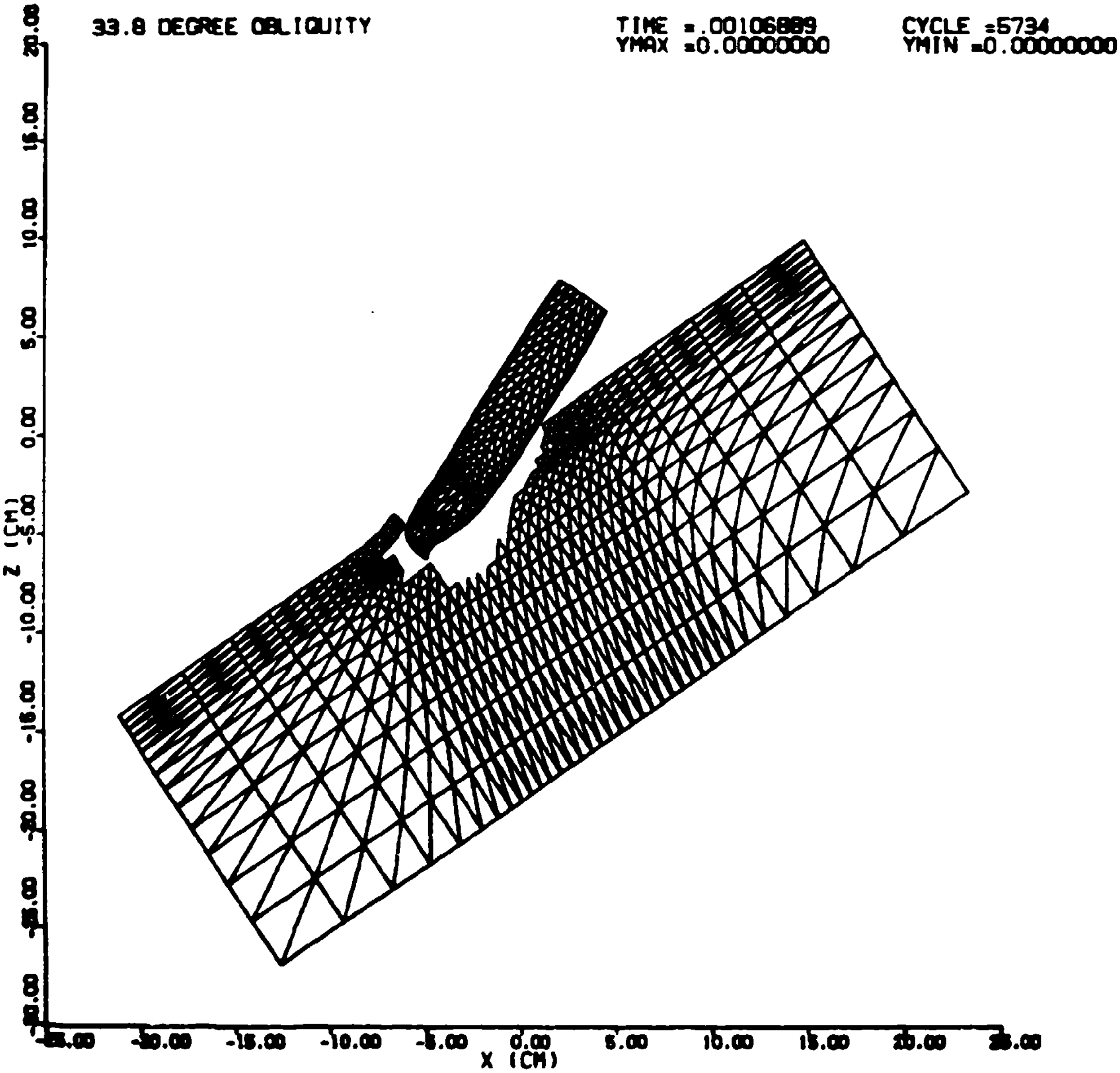

Figure A14. Deformation Profile for 33.8° Obliquity at T = 106.9 μs

APPENDIX B

Input Data for EPIC-3 Preprocessor for 33.8° Obliquity

```
.080 PROJECTILE. V=750 FPS. IMPACT ANGLE=56.2 DEG (FROM HORIZONTAL)
  606     1     0     1     1     0     0     0     1     4     0    15
    1     11045 STEEL RC 29
  .000725    830000. 23038000. 42693000. 72513000.        1.2         .2
 11500000.   180000.   240000.       .08  1000000.         0.         1.
     999.       999.      999.       70.
    2     1TRITONAL EXPLOSIVE SIMULANT
  .000136    999999.    20163.        0.        0.         0.         .2
   15048.       309.      309.        1.  1000000.         0.         1.
     999.       999.      999.       70.
    3     4CONCRETE (OSBORN REPORT) 6300 PSI COMPRESSIVE STRENGTH
  .000206    560000.       70.      999.      999.       0.40         .2
  1542000.        0.        0.      999.      630.         0.         1.
    4112.       .002   116000.        .1   305000.         .2    875000.
 11364000.        .2     6300.   -.03333        1.      .3333      30.67

       1.         1.        1.        0.        0.        0.0        0.
    2
    4     0     2     1   6.733     6.363        1.
     .162      .325      .487      .567
     .170      .341      .511      .591
    6.733     6.733     6.733     6.733
    6.363     6.363     6.363     6.363
    2
    4     0     2     1   6.000     5.627        1.
     .176      .353      .529      .609
     .180      .360      .540      .620
    6.000     6.000     6.000     6.000
    5.627     5.627     5.627     5.627
    2
    4     0     5     1   5.260     3.786        1.
     .182      .363      .545      .625
     .182      .363      .545      .625
    5.260     5.260     5.260     5.260
    3.786     3.786     3.786     3.786
    2
    4     0     2     1   3.451     3.132        1.
     .181      .362      .543      .623
     .177      .355      .532      .612
    3.451     3.451     3.451     3.451
    3.132     3.132     3.132     3.132
    2
    4     0     2     1   2.828     2.539        1.
     .171      .343      .514      .594
     .164      .328      .492      .572
    2.828     2.828     2.828     2.828
    2.539     2.539     2.539     2.539
    2
    4     0     2     1   2.263     2.000        1.
     .157      .313      .470      .550
     .148      .296      .444      .524
    2.263     2.263     2.263     2.263
    2.000     2.000     2.000     2.000
    3
    4     0     3     1    .524        0.        2.         0.
     .148      .296      .444      .524
    1.000      .600      .156        0.

       1.         1.        1.      -1.5        0.      -33.8         0.
    4     2
   37    13    13     9    12     1    1.30    .35294      1.02       .9      1.20
     -8.5         0.        0.       8.5       5.6        -6.
```

```
   2
   4     1     1     1     0     1
   2
   4     1    13    46     1     0
   2     2     2     1
   3
   4     1         676     1     0
   2     2     2     1

   4     2
  36    12    14   856           3

   2     4     3   855   859  2328   810    30     1     0        .10    30000.     3.
   4     0    11
 859   885     1
 896   922     1
 933   959     1
 970   996     1
1007  1033     1
1044  1070     1
1081  1107     1
1118  1144     1
1155  1181     1
1192  1218     1
1414  1440     1
1451  1477     1
1488  1514     1
1525  1551     1
1562  1588     1
1599  1625     1
1636  1662     1
1673  1699     1
1710  1736     1
1747  1773     1
1969  1995     1
2006  2032     1
2043  2069     1
2080  2106     1
2117  2143     1
2154  2180     1
2191  2217     1
2228  2254     1
2265  2291     1
2302  2328     1

         0.         0.         0.
         0.         0.     -9000.         0.         0.         0.  .0000001
```

REFERENCES

1. E. T. Roecker, et. al., BRL Report in progress.

2. G. R. Johnson, D. J. Vavrick, and D. D. Colby, "Further Development of EPIC-3 for Anisotropy, Sliding Surfaces, Plotting and Material Models," Ballistic Research Laboratory, ARBRL-CR-00429, May 1980 (AD B048305L).

3. G. R. Johnson, Honeywell Inc., Defense Systems Division, Private communication.

4. J. J. Osborn and D. A. Matuska, "Dynamic Response of a Kinetic Energy Penetrator, Vol II. - Hydrocode Analysis," AFATL TR 78-24, March 1978.

5. V. G. Gregson, Jr., "A Shock Wave Study of Fondu-Frye WA-1 and a Concrete," DNA report 2797F, February 1972.

6. J. Chinn and R. M. Zimmerman, "Behavior of Plain Concrete Under Various High Triaxial Compression Loading Conditions," AFWL TR 64-163, August 1965.

7. D. McHenry and J. Karni, "Strength of Concrete Under Combined Tensile and Compressive Stress," American Concrete Institute, page 54, 10 April 1958.

8. K. E. Crawford, C. J. Higgins, and E. H. Bultmann, "The Air Force Manual for Design and Analysis of Hardened Structures," AFWL TR-74-102, October 1974.

DISTRIBUTION LIST

Copies	Organization
12	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22314
1	Director Defense Advanced Research Projects Agency ATTN: Tech Info 1400 Wilson Boulevard Arlington, VA 22209
1	Director Defense Nuclear Agency Washington, DC 20305
1	Deputy Assistant Secretary of the Army (R&D) Department of the Army Washington, DC 20310
2	Director US Army BMD Advanced Technology Center ATTN: ATC-M, S. Brockway ATC-RN, P. Boyd PO Box 1500 Huntsville, AL 35804
1	HQDA (DAMA-ARP) WASH DC 20310
1	HQDA (DAMA-MS) WASH DC 20310
2	Commander US Army Engineer Waterways Experiment Station ATTN: Dr. P. Hadala Dr. B. Rohani PO Box 631 Vicksburg, MS 39181
1	Commander US Army Materiel Development and Readiness Command ATTN: DRCDMD-ST 5001 Eisenhower Avenue Alexandria, VA 22333

Copies	Organization
9	Commander Armament R&D Center US Army AMCCOM ATTN: DRSMC-TD(D), Dr. Weigle DRSMC-LC(D), Dr. J. Frasier DRSMC-TSS DRSMC-LCF(D), G. Demitrack DRSMC-LCA(D), G. Randers-Pehrson DRSMC-SCS-M(D), R. Kwatnoski DRSMC-LCU(D), E. Barrieres DRSMC-SCM(D), Dr.E. Bloore Dover, NJ 07801
2	Director US Army AMCCOM Benet Weapons Laboratory ATTN: DRSMC-LCB-TL(D) Dr. Joseph E. Flaherty Watervliet, NY 12189
1	Commander US Army AMCCOM ATTN: DRSMC-LEP-L(R) Rock Island, IL 61299
1	Commander US Army Aviation Research and Development Command ATTN: DRDAV-E 4300 Goodfellow Blvd. St. Louis, MO 63120
1	Director US Army Air Mobility Research and Development Laboratory Ames Research Center Moffett Field, CA 94035
1	Commander US Army Communications Research and Development Command ATTN: DRSEL-ATDD Fort Monmouth, NJ 07703

DISTRIBUTION LIST

Copies	Organization
1	Commander US Army Electronics Research and Development Command Technical Support Activity ATTN: DELSD-L Fort Monmouth, NJ 07703
1	Commander US Army Missile Command ATTN: DRSMI-R Redstone Arsenal, AL 35898
1	Commander US Army Tank Automotive Command ATTN: DRSTA-TSL Warren, MI 48090
1	Commander TARADCOM Tank-Automotive Systems Laboratory ATTN: T. Dean Warren, MI 48090
6	Commander US Army Materials and Mechanics Research Center ATTN: DRXMR-T, Mr. J. Bluhm Mr. J. Mescall Dr. M. Lenoe R. Shea F. Quigley DRXMR-ATL Watertown, MA 02172
2	Commander US Army Research Office ATTN: Dr. E. Saibel Dr. G. Mayer PO Box 12211 Research Triangle Park NC 27709
1	Director US Army TRADOC Systems Analysis Activity ATTN: ATAA-SL White Sands Missile Range NM 88002
1	Office of Naval Research Department of the Navy ATTN: Code ONR 439, N. Perrone 800 North Quincy Street Arlington, VA 22217
3	Commander Naval Air Systems Command ATTN: AIR-604 Washington, DC 20360
1	AFWL/SUL Kirtland AFB, NM 87117
2	Commander Naval Air Development Center, Johnsville Warminster, PA 18974
1	Commander Naval Missile Center Point Mugu, CA 93041
2	Commander Naval Ship Engineering Center Washington, DC 20362
1	Commander David W. Taylor Naval Ship Research & Development Center ATTN: Code 1740.4, R. A. Gramm Bethesda, MD 20084

DISTRIBUTION LIST

Copies	Organization
3	Commander Naval Surface Weapons Center ATTN: Dr. W. G. Soper Mr. N. Rupert Code G35, D. C. Peterson Dahlgren, VA 22448
10	Commander Naval Surface Weapons Center ATTN: Dr. S. Fishman (2 cys) Code R-13, F. J. Zerilli K. Kim E. T. Toton M. J. Frankel Code U-11, J. R. Renzi R. S. Gross Code K-22, F. Stecher J. Etheridge Silver Spring, MD 20910
3	Commander Naval Weapons Center ATTN: Code 31804, Mr. M. Smith Code 326, Mr. P. Cordle Code 3261, Mr. T. Zulkoski China Lake, CA 93555
6	Commander Naval Weapons Center ATTN: Code 3181, John Morrow Code 3261, Mr. C. Johnson Code 3171, Mr. B. Galloway Code 3831, Mr. M. Backman Mr. R.E. VanDevender Dr. O. E. R. Heimdahl China Lake, CA 93555
2	Commander Naval Research Laboratory ATTN: Dr. C. Sanday Dr. H. Pusey Washington, DC 20375
2	Superintendent Naval Postgraduate School ATTN: Dir of Lib Dr. R. Ball Monterey, CA 93940
3	Long Beach Naval Shipyard ATTN: R. Kessler T. Eto R. Fernandez Long Beach, CA 90822
1	HQ USAF/SAMI Washington, DC 20330
1	AFIS/INOT Washington, DC 20330
10	ADTC/DLJW (LT K. Ols) Eglin AFB, FL 32542
10	ADTC/DLYV (Mr. J. Collins) Eglin AFB, FL 32542
1	AFATL/DLYV Eglin AFB, FL 32542
1	AFATL/DLODL Eglin AFB, FL 32542
1	AFATL/CC Eglin AFB, FL 32542
1	AFATL/DLODR Eglin AFB, FL 32542
1	HQ, PACAF/OA Hickam AFB Honolulu, HA 96853
1	OOALC/MMWMC Hill AFB, UT 84406
1	HQ TAC/DRA Langley AFB, VA 23665
1	TAC/INAT Langley AFB, VA 23665

DISTRIBUTION LIST

Copies	Organization
1	AUL-LSE 71-249 Maxwell AFB, AL 36112
1	AFWAL/MLLN (Mr. T. Nicholas) Wright-Patterson AFB, OH 45433
1	ASD/ENESS (S. Johns) Wright-Patterson AFB, OH 45433
1	ASD/ENFEA Wright-Patterson AFB, OH 45433
1	ASD/XRP Wright-Patterson AFB, OH 45433
1	HQUSAFE/DOQ APO New York 09012
1	COMIPAC/I-32 Box 38 Camp H. I. Smith, HI 96861
10	Battelle Pacific Northwest Laboratories PO Box 999 ATTN: G. D. Marr Richland, WA 99352
1	Lawrence Livermore Laboratory ATTN: Dr. R. Werne P.O. Box 808 Livermore, CA 94550
6	Los Alamos Scientific Laboratory PO Box 1663 ATTN: Dr. R. Karpp Dr. J. Dienes Dr. J. Taylor Dr. E. Fugelso Dr. D. E. Upham Dr. R. Keyser Los Alamos, NM 87545
6	Sandia Laboratories ATTN: Dr. R. Woodfin Dr. M. Sears Dr. W. Herrmann Dr. L. Bertholf Dr. A. Chabai Dr. C. B. Selleck Albuquerque, NM 87115
1	Headquarters National Aeronautics and Space Administration Washington, DC 20546
1	Jet Propulsion Laboratory 4800 Oak Grove Drive ATTN: Dr. Ralph Chen Pasadena, CA 91103
1	Director National Aeronautics and Space Administration Langley Research Center Langley Station Hampton, VA 23365
1	US Geological Survey 2255 N. Gemini Drive ATTN: Dr. D. Roddy Flagstaff, AZ 86001
1	AAI Corporation PO Box 6767 ATTN: R. L. Kachinski Baltimore, MD 21204
1	Aerojet Ordnance Company 9236 East Hall Road Downey, CA 90241
1	Aeronautical Research Associates of Princeton, Inc. 50 Washington Road P.O. Box 2229 Princeton, NJ 08540

DISTRIBUTION LIST

Copies	Organization
1	Aerospace Corporation 2350 E. El Segundo Blvd. ATTN: Mr. L. Rubin El Segundo, CA 90245
1	AVCO Systems Division 201 Lowell Street ATTN: Dr. Reinecke Wilmington, MA 01887
1	Lawrence Livermore Laboratory ATTN: Dr. G. Goudreau P.O. Box 808 Livermore, CA 94550
4	Boeing Aerospace Company ATTN: Mr. R. G. Blaisdell (M.S. 40-25) Dr. N. A. Armstrong C. J. Artura (M.S. 8C-23) Dr. B. J. Henderson (M.S. 43-12) Seattle, WA 98124
2	Brunswick Corporation 4300 Industrial Avenue ATTN: P. S. Chang R. Grover Lincoln, NE 68504
1	Computer Code Consultants, Inc. 1680 Camino Redondo ATTN: Dr. Wally Johnson Los Alamos, NM 87544
1	Dresser Center PO Box 1407 ATTN: Dr. M. S. Chawla Houston, TX 77001
1	Effects Technology, Inc. 5383 Hollister Avenue Santa Barbara, CA 93111

Copies	Organization
1	Electric Power Research Institute PO Box 10412 ATTN: Dr. George Sliter Palo Alto, CA 94303
1	FMC Corporation Ordnance Engineering Division San Jose, CA 95114
1	Ford Aerospace and Communications Corporation Ford Road, PO Box A ATTN: L. K. Goodwin Newport Beach, CA 92660
1	General Dynamics PO Box 2507 ATTN: J. H. Cuadros Pomona, CA 91766
1	General Electric Company Lakeside Avenue ATTN: D. Graham, Rm 1311 Burlington, VT 05401
1	President General Research Corporation ATTN: Lib McLean, VA 22101
1	Goodyear Aerospace Corporation 1210 Massillon Road Akron, OH 44315
1	H. P. White Laboratory 3114 Scarboro Road Street, MD 21154
5	Honeywell, Inc. Government and Aerospace Products Division ATTN: Mr. J. Blackburn Dr. G. Johnson Mr. R. Simpson Mr. K. H. Doeringsfeld Dr. D. Vavrick 600 Second Street, NE Hopkins, MN 55343

DISTRIBUTION LIST

Copies	Organization
1	Hughes Aircraft Corporation ATTN: Mr. W. Keppel MS M-5, Bldg 808 Tucson, AZ 85706
2	Kaman Sciences Corporation 1500 Garden of the Gods Road ATTN: Dr. P. Snow Dr. D. Williams Colorado Springs, CO 80907
1	Lockheed Palo Alto Research Laboratory 3251 Hanover Street ATTN: Org 5230, Bldg 201 Mr. R. Robertson Palo Alto, CA 94394
1	Lockheed Missiles and Space Company PO Box 504 ATTN: R. L. Williams Dept. 81-11, Bldg 154 Sunnyvale, CA 94086
1	Materials Research Laboratory, Inc. 1 Science Road Glenwood, IL 60427
2	McDonnell-Douglas Astronautics Company 5301 Bolsa Avenue ATTN: Dr. L. B. Greszczuk Dr. J. Wall Huntington Beach, CA 92647
1	New Mexico Institute of Mining and Technology ATTN: TERA Group Socorro, NM 87801
1	Northrup Corporation 3901 W. Broadway ATTN: R. L. Ramkumar Hawthorne, CA 90250
1	Nuclear Assurance Corporation 24 Executive Park West ATTN: T. C. Thompson Atlanta, GA 30245
2	Orlando Technology, Inc. PO Box 855 ATTN: Mr. J. Osborn Mr. D. Matuska Shalimar, FL 32579
1	Lawrence Livermore Laboratory ATTN: Dr. M. L. Wilkins P.O. Box 808 Livermore, CA 94550
1	Rockwell International Missile Systems Division ATTN: A. R. Glaser 4300 E. Fifth Avenue Columbus, OH 43216
3	Schumberger Well Services Perforating Center ATTN: J. E. Brooks J. Brookman Dr. C. Aseltine PO Box A Rosharon, TX 77543
1	Science Applications, Inc. 101 Continental Building Suite 310 El Segundo, CA 90245
1	Lawrence Livermore Laboratory ATTN: Dr. J. O. Hallquist P.O. Box 808 Livermore, CA 94550
1	Systems, Science and Software PO Box 1620 ATTN: Dr. R. Sedgwick La Jolla, CA 92037

DISTRIBUTION LIST

Copies	Organization
2	TRW One Space Park, R1/2120 ATTN: D. Ausherman M. Bronstein Redondo Beach, CA 90278
1	United Technologies Research Center 438 Weir Street ATTN: P. R. Fitzpatrick Glastonbury, CT 06033
1	US Steel Corporation Research Center 125 Jamison Center Monroeville, PA 15146
1	VPI & SU 106C Norris Hall ATTN: Dr. M. P. Kamat Blacksburg, VA 24061
2	Vought Corporation PO Box 225907 ATTN: Dr. G. Hough Dr. Paul M. Kenner Dallas, TX 75265
1	Westinghouse, Inc. PO Box 79 ATTN: J. Y. Fan W. Mifflin, PA 15122
1	Drexel Institute of Technology Department of Mechanical Engr. ATTN: Dr. P. C. Chou 32d and Chestnut Streets Philadelphia, PA 19104
5	Southwest Research Institute Dept. of Mechanical Sciences ATTN: Dr. U. Lindholm Dr. W. Baker Dr. R. White Dr. M. F. Kanninen Dr. C. Anderson 8500 Culebra Road San Antonio, TX 78228

Copies	Organization
4	SRI International 333 Ravenswood Avenue ATTN: Dr. L. Seaman Dr. L. Curran Dr. D. Shockey Dr. A. L. Florence Menlo Park, CA 94025
2	University of Arizona Civil Engineering Department ATTN: Dr. D. A. DaDeppo Dr. R. Richard Tucson, AZ 85721
1	University of Arizona School of Engineering ATTN: Dean R. Gallagher Tucson, AZ 85721
1	University of California ATTN: Dr. N. Ziv 504 Hilgard Avenue Los Angeles, CA 90024
1	University of California Department of Physics ATTN: Dr. Harold Lewis Santa Barbara, CA 93106
2	University of California College of Engineering ATTN: Prof. W. Goldsmith Dr. A. G. Evans Berkeley, CA 94720
2	University of Delaware Department of Mechanical Engineering ATTN: Prof. J. Vinson Prof. B. Pipes Newark, DE 19711
1	University of Denver Denver Research Institute ATTN: Mr. R. F. Recht 2390 S. University Blvd. Denver, CO 80210

DISTRIBUTION LIST

Copies	Organization
2	University of Florida Department of Engineering Sciences ATTN: Dr. R. L. Sierakowski Dr. L. E. Malvern Gainesville, FL 32601
1	University of Oklahoma School of Aerospace, Mechanical and Nuclear Engineering ATTN: Dr. C. W. Bert Norman, OK 73069
1	Commander Armament R&D Center US Army AMCCOM ATTN: DRSMC-TDC(D) Dover, NJ 07801
2	Commandant US Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905
1	Commander US Army Missile Command ATTN: DRSMI-RBL Redstone Arsenal, AL 35898
1	Commander US Army Missile Command ATTN: DRSMI-YDL Redstone Arsenal, AL 35898
3	Commander Naval Sea Systems Command Navy Department ATTN: SEA-62R SEA-62Y SEA 9961 Washington, DC 20360
1	HQ, PACAF/DOOQ Hickam AFB Honolulu, HA 96853

Copies	Organization
	<u>Aberdeen Proving Ground</u>
	Dir, USAMSAA ATTN: DRXSY-D DRXSY-MP, H. Cohen
	Cdr, USATECOM ATTN: DRSTE-TO-F
	Dir, MTD ATTN: Mr. W. Pless Mr. S. Keithley
	Cdr, CRDC, AMCCOM ATTN: DRSMC-CLB-PA DRSMC-CLN DRSMC-CLJ-L

USER EVALUATION OF REPORT

Please take a few minutes to answer the questions below; tear out this sheet, fold as indicated, staple or tape closed, and place in the mail. Your comments will provide us with information for improving future reports.

1. BRL Report Number ______________________________

2. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which report will be used.)

____

____

____

3. How, specifically, is the report being used? (Information source, design data or procedure, management procedure, source of ideas, etc.) ______________________________

____

____

4. Has the information in this report led to any quantitative savings as far as man-hours/contract dollars saved, operating costs avoided, efficiencies achieved, etc.? If so, please elaborate.

____

____

5. General Comments (Indicate what you think should be changed to make this report and future reports of this type more responsive to your needs, more usable, improve readability, etc.) ____________

____

____

____

6. If you would like to be contacted by the personnel who prepared this report to raise specific questions or discuss the topic, please fill in the following information.

Name: ______________________________

Telephone Number: ______________________________

Organization Address: ______________________________

____

____